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ABSTRACT

Optical and electromagnetic fundamentals are presented in this fourth unit of the Project Physics text for use by senior high students. Development of the wave theory in the first half of the 19th Century is described to deal with optical problems at the early stage. Following explanations of electric charges and forces, field concepts are introduced in connection with electrons, currents, potential differences, Oersted's discovery, Ampere's work, and moving charges in magnetic fields. Faraday's lines of force are used to analyze electromagnetic induction and its applications as well as modern civilization under the influence of scientific discoveries. Further discussions of field theories are made for electromagnetic radiation, taking into account Maxwell's theories, Hertz's experiment, wave propagation, electromagnetic spectra, and ether concept. Historical developments are stressed in the overall explanation. Problems with their answers are provided in two categories: study guide and end of section questions. Also included are related illustrations for explanation purposes and a chart of renowned people's life spans between 1700 and 1900. The work of Harvard Project Physics has been financially supported by: the Carnegie Corporation of New York, the Ford Foundation, the National Science Foundation, the Alfred P. Sloan Foundation, the United States Office of Education, and Harvard University. (CC)

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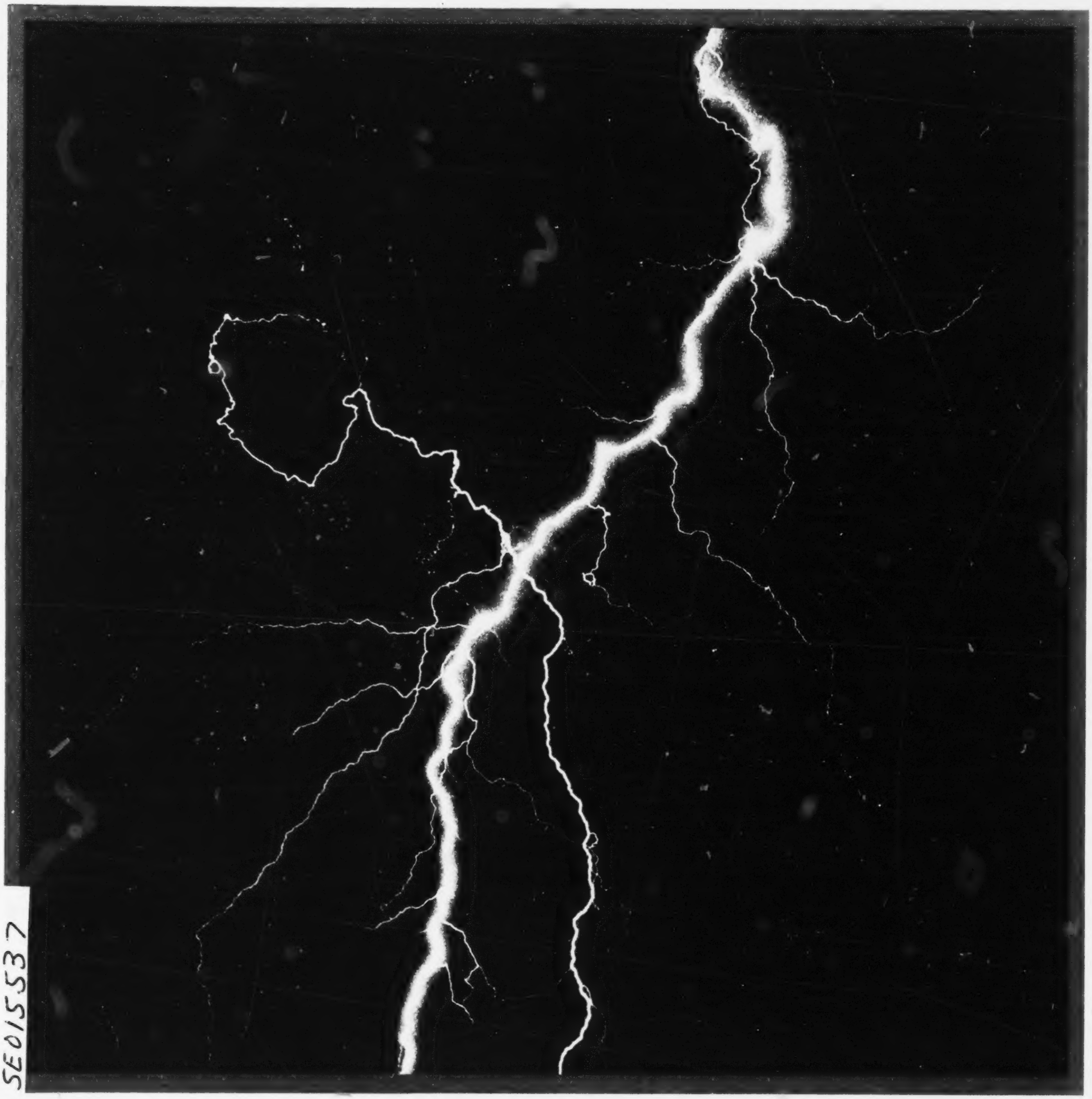
Project Physics **Text** 4

An Introduction to Physics

Light and Electromagnetism



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Project Physics **Text**

An Introduction to Physics 4 Light and Electromagnetism

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Welcome to the study of physics. This volume, more of a student's guide than a text of the usual kind, is part of a whole group of materials that includes a student handbook, laboratory equipment, films, programmed instruction, readers, transparencies, and so forth. Harvard Project Physics has designed the materials to work together. They have all been tested in classes that supplied results to the Project for use in revisions of earlier versions.

The Project Physics course is the work of about 200 scientists, scholars, and teachers from all parts of the country, responding to a call by the National Science Foundation in 1963 to prepare a new introductory physics course for nationwide use. Harvard Project Physics was established in 1964, on the basis of a two-year feasibility study supported by the Carnegie Corporation. On the previous pages are the names of our colleagues who helped during the last six years in what became an extensive national curriculum development program. Some of them worked on a full-time basis for several years; others were part-time or occasional consultants, contributing to some aspect of the whole course; but all were valued and dedicated collaborators who richly earned the gratitude of everyone who cares about science and the improvement of science teaching.

Harvard Project Physics has received financial support from the Carnegie Corporation of New York, the Ford Foundation, the National Science Foundation, the Alfred P. Sloan Foundation, the United States Office of Education and Harvard University. In addition, the Project has had the essential support of several hundred participating schools throughout the United States and Canada, who used and tested the course as it went through several successive annual revisions.

The last and largest cycle of testing of all materials is now completed; the final version of the Project Physics course will be published in 1970 by Holt, Rinehart and Winston, Inc., and will incorporate the final revisions and improvements as necessary. To this end we invite our students and instructors to write to us if in practice they too discern ways of improving the course materials.

The Directors
Harvard Project Physics

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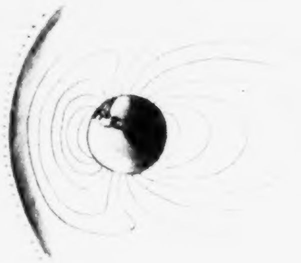
Prologue The conviction that the world, and all that is in it, consists of matter in motion drove scientists to search for mechanical models that could account for light and electromagnetism. This search, what was discovered and the changes these discoveries initiated in science, in technology and in society form the subject of this volume. In this prologue we sketch the development of some of these models and briefly indicate the effect of these developments on our present ideas of the physical world.

During the seventeenth and eighteenth centuries there were two competing models for light, one depicting light as particles, the other depicting light as waves. Both models were constructed with the Newtonian components of matter and motion. The wave model won general acceptance, not because it fitted the Newtonian scheme better than the particle model, but because it was better able to account for newly discovered optical effects. Chapter 13 tells the story of the triumph of the wave theory of light in the first half of the nineteenth century. The wave theory maintained its supremacy until the early part of the twentieth century when it was found that neither waves nor particles were sufficient to account for the behavior of light.

As experiments established that electric and magnetic forces have some characteristics in common with gravitational forces, theories of electricity and magnetism were developed which were modeled on Newton's treatment of gravitation. The assumption that there are forces between electrified and magnetized bodies which vary inversely with the square of the distance was found to account for many observations. The drafters of these theories assumed that bodies can exert forces over a distance without the necessity for one body to touch another.

Although action-at-a-distance theories were remarkably successful in providing a quantitative explanation for some aspects of electromagnetism, these theories did not at the time provide a comprehensive explanation. Instead, the means of description that became widely accepted by the end of the nineteenth century, and that is now generally believed to be the best way to discuss all physical forces, is based on the idea of fields, an idea that we introduce in Chapter 14 and develop further in the last chapter of the unit.

Many scientists felt that action-at-a-distance theories, however accurate in prediction, failed to give a satisfactory physical explanation for how one body exerts a force on another. Newton himself was reluctant to assume that one body can act on another through empty space. In a letter to



It was inconceivable to many scientists that one body could directly affect another across empty space. They devised a variety of schemes to fill the space in between with something that would transmit the effect first with material "ether," -- later with mathematical "fields." Some of these schemes are illustrated on the opposite page: Descartes, 17th century (bottom left); Euler, 18th century (top); Maxwell, 19th century (middle right). Above is a drawing copied from The New York Times (1967) representing the earth's magnetic field, which is distorted by a flow of charged particles from the sun.

Richard Bentley he wrote:

This letter is reproduced exactly as Newton wrote it.

> Tis unconceivable to me that inanimate brute matter should (without the mediation of something else wch is not material) operate upon & affect other matter wthout mutual contact; ... And this is one reason why I desired you would not ascribe innate gravity to me. That gravity should be innate inherent & essential to matter so yt one body may act upon another at a distance through a vacuum wthout the mediation of any thing else by & through wch their action or force may be conveyed from one point to another is to me so great an absurdity that I beleive no man who has in philosophical matters any competent faculty of thinking can ever fall into it.

Some seventeenth-century scientists, less cautious in their published speculations than Newton, proposed that objects are surrounded by atmospheres that extend to the most distant regions and serve to transmit gravitational, electric and magnetic forces from one body to another. The atmospheres proposed at this time were not made a part of a quantitative theory. In the nineteenth century, when the idea of an all-pervading atmosphere was revived, numerous attempts were made to develop mathematically the properties of a medium that would transmit the waves of light. The name "luminiferous ether" was given to this hypothetical "light-bearing" substance.

The rapid discovery of new electrical and magnetic effects in the first half of the nineteenth century acted as a strong stimulus to model building. Michael Faraday (1791-1867), who made many of the important discoveries, developed a model that assigned lines of force to the space surrounding electrified and magnetized bodies. Faraday showed how these lines of force could be used to account for many electromagnetic effects.

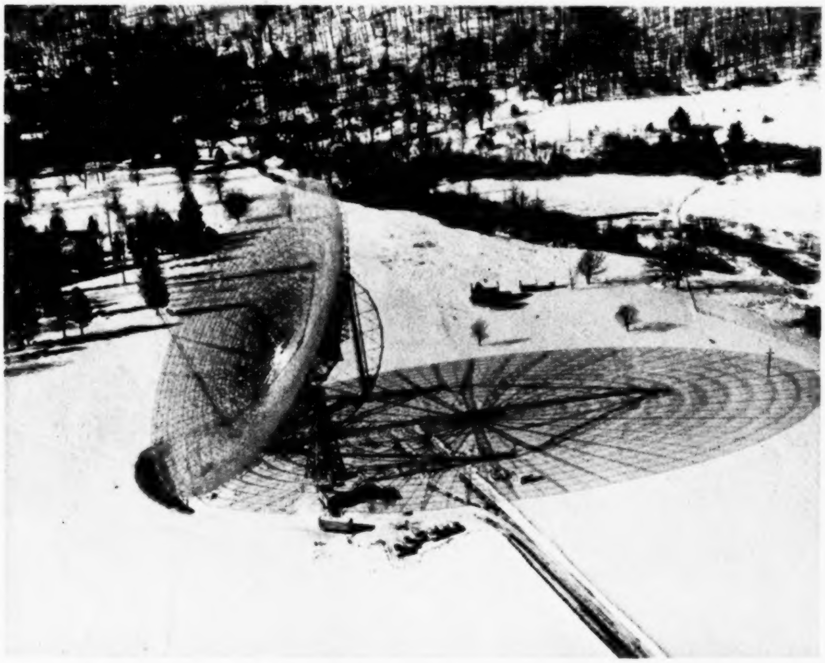
William Thomson (Lord Kelvin) was a Scottish mathematical physicist who contributed to the fields of electricity, mechanics and thermodynamics and to such practical developments as an improved ship's compass and the first Atlantic cable. The Kelvin scale of absolute temperature is named for him.

In a paper he wrote at age 17, William Thomson (1824-1907) showed how the equations used to formulate and solve a problem in electrostatics could also be used to solve a problem in the flow of heat. At that time electrostatics was most simply and effectively treated by considering that electrical forces can act at a distance, while the flow of heat was generally held to result from the action of parts that touch. With this paper Thomson showed that the same mathematical formulation could be used for theories based on completely different physical assumptions. Perhaps, then, it was more important to find a correct set of equations than it was to choose a particular mechanical model.

James Clerk Maxwell (1831-1879), inspired by Faraday's physical models and by Thomson's mathematical demonstrations, undertook the task of developing a mathematical theory of electromagnetism. From the assumption of an imaginary ether filled with gears and idle wheels, Maxwell gradually worked his way to a set of equations for electric and magnetic fields. These equations were later found to be remarkably successful. Not only did the equations describe accurately the electric and magnetic effects already known to occur, but they led Maxwell to predict new effects based on the idea that light is a form of electromagnetic wave.

See Maxwell's article "Action at a Distance" in Project Physics Reader 4.

The field concept, in conjunction with the concept of energy, provides a way of treating the action of one body on another without speaking of action at a distance or of a material medium that transmits the action from one body to another. The concept of a field has proved its utility over and over again during the twentieth century.



Radio telescope at the National Radio Astronomy Observatory, Greenbank, West Virginia.

Chapter 13 Light

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13.1 Introduction. What is light? At first glance, this may seem to be a rather trivial question. After all, there is hardly anything that is more familiar to us. We see by means of light. We also live by light, for without it there would be no photosynthesis, and photosynthesis is the basic source of energy for most forms of life on earth. Light is the messenger which brings us most of our information about the world around us, both on the earth and out to the most distant reaches of space. Because our world is largely defined by light, we have always been fascinated by its behavior. From the beginning of recorded history men have asked themselves questions about light. How fast does it travel? How does it manage to travel across empty space? What is color?

To the physicist, light is a form of energy. He can describe light by measurable values of wavelengths and frequencies and intensity of the beam. To him, as to all people, light also means brightness and shade, the beauty of summer flowers and fall foliage, of red-gold sunsets and of the canvases painted by master artists. These are really two ways of looking at light: one way is to regard its measurable aspects—which has been enormously fruitful in physics and in technology. The other is to ask about the emotional responses in us when we view the production of light in nature or art. Still another way of considering light is in terms of the biophysical process of vision. The physical, biophysical, and psychological aspects of light are closely related.

Because these aspects of light are not easily separated, problems raised about light in the early history of science were more subtle and more elusive than those associated with most other aspects of our physical experience. Early ideas on its nature were confused by a failure to distinguish between light and vision. This confusion is still evident in young children. When playing hide-and-go-seek, some of them "hide" by covering their eyes with their hands; apparently they think that they cannot be seen when they cannot see. This almost instinctive association of vision with light persists into the language of the adult world. We talk about the sun "peeping out of the clouds" or the stars "looking down."

Some of the Greek philosophers believed that light travels in straight lines at high speed, and that it contains particles which stimulate the sense of vision when they enter the eye. For centuries after the Greek era during which limited attention was paid to the nature of light, the particle model persisted. However, around 1500 Leonardo da Vinci, noting a similarity between sound echoes and the reflection of light,

Behold the Light emitted from the Sun,
What more familiar, and what more unknown;
While by its spreading Radiance it reveals
All Nature's Face, it still it self conceals ...
How soon th'Effulgent Emanations fly
Thro' the blue Gulph of interposing Sky!
How soon their Lustre all the Region fills,
Smiles on the Vallies, and adorns the Hills!
Millions of Miles, so rapid is their Race,
To cheer the Earth, they in few Moments pass.
Amazing Progress! At its utmost Stretch,
What human Mind can this swift Motion reach?

Richard Blackmore, Creation II, 1715, 386-399.

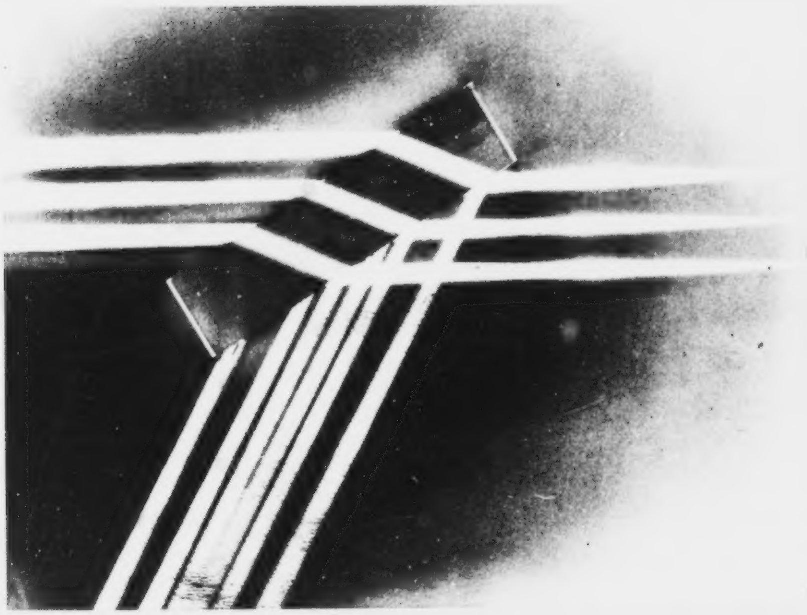
speculated that light, like sound, might have a wave character.

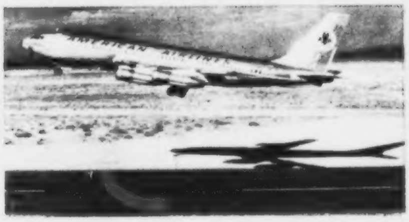
A decided difference of opinion emerged among scientists of the seventeenth century about the nature of light. Some, including Newton, favored a model largely based on the idea of light as a stream of particles. Others, including Huygens, supported a wave model. By the late nineteenth century, however, there appeared to be overwhelming evidence that the observed characteristics of light could be explained by assuming that it had the nature of a wave motion; that is, by assuming a wave model. In this chapter we shall look at the question "How appropriate is a wave model in explaining the observed behavior of light?" That is, we shall take the wave model as a hypothesis, and examine the evidence that supports it. We must bear in mind that any scientific model, hypothesis or theory has two chief functions—to explain what is known, and to make predictions that can be subjected to experimental test. We shall look at both of these aspects of the wave model. The result will be very curious. The wave model turns out to work splendidly for all the properties of light known before the twentieth century. But in Chapter 18 we will find that for some purposes we must adopt instead a particle model. Then in Chapter 20 we will combine both models, joining together two apparently opposite theories!

We have already mentioned that light travels in straight lines and at high speed. Our daily use of mirrors convinced us that light can also be reflected. There are other characteristics of light—for example, it can be refracted, and it shows the phenomena of interference and diffraction. All of these properties you have studied earlier, when looking at the behavior of waves in Chapter 12. It would therefore be well for you to refresh your memory about the basic ideas of that chapter before going on to the study of light. We shall, however, look at some additional phenomena of light—dispersion, polarization and scattering—which so far we have considered either not at all or in minimum detail in the earlier discussion. As we shall see, these also fit into our wave model, and in fact constitute strong experimental support for it. Before going on to a discussion of these various characteristics of light's behavior and how they provide evidence in support of our hypothesis of a wave model for light, we shall first consider the propagation of light and two characteristics—reflection and refraction—which can be explained by both a corpuscular (particle) model and a wave model.

13.2 Propagation of light. There is ample evidence that light travels in straight lines. The fact that one cannot see

Light Beams Travel in Straight Lines.

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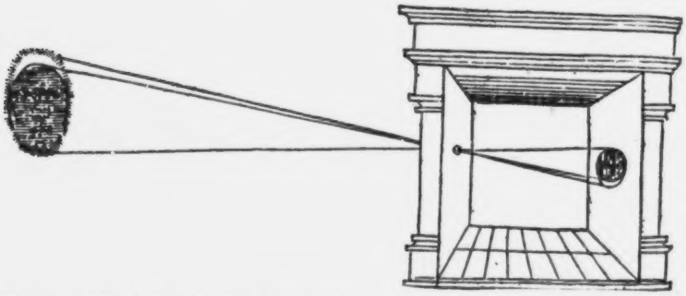
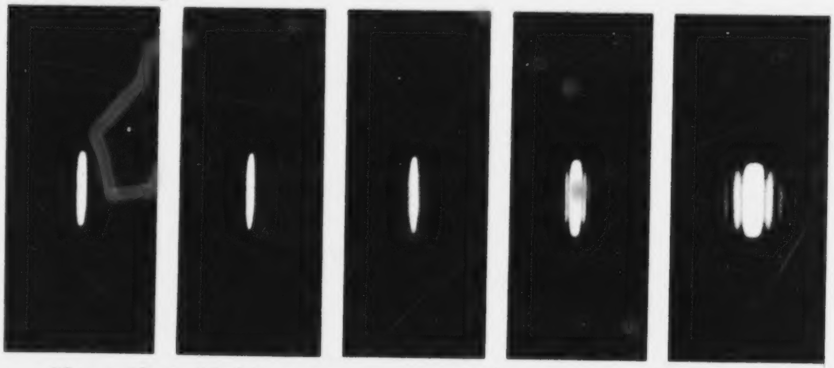
"around the corner" of an obstacle is one obvious example. The outline of a shadow cast by the sun is but one example of the sharply defined shadows cast by a large but very distant source. Similarly, sharp shadows are cast by a closer source of small dimensions. The distant sun or the nearby small source are approximately point sources of light; it is from such point sources that we get sharp shadows. Before the invention of the modern camera with its lens system, a light-tight box with a pinhole in the center of one face was widely used. As the camera obscura, it was highly popular in the Middle Ages. Leonardo da Vinci probably used it as an aid in his sketching. In one of his manuscripts he says that "a small aperture in a window shutter projects on the inner wall of the room an image of the bodies which are beyond the aperture," and he includes a sketch to show how the straight-line propagation of light explains the formation of an image.

"Camera obscura" is a Latin phrase meaning "dark chamber."



First published illustration of a camera obscura: observing a solar eclipse in January 1544, from a book by the Dutch physician and mathematician Gemma Frisius.

It is often convenient to use a straight line to represent the direction in which light travels. The convenient pictorial device, an infinitely thin ray of light, is useful for thinking about light but it does not correspond to anything that actually exists. A light beam emerging from a good-sized hole in a screen is as wide as the hole. You might expect that if we made the hole extremely small we would get a very narrow beam of light—ultimately, just a ray. But we don't! Diffraction effects (such as you have already observed for water and sound waves) appear when the beam of light passes through a small hole. So a ray of light, pictorially useful, cannot be produced in practice. But we can still use the idea to represent the direction in which a train of parallel waves is traveling.



An attempt to produce a "ray" of light. To make the pictures at the right, a parallel beam of red light was directed through increasingly narrow slits to a photographic plate. The slit widths, from left to right, were 1.5 mm, 0.7 mm, 0.4 mm, 0.2 mm and 0.1 mm. The results are similar to those shown for water ripples on p. 133 of Unit 3 (Fig. 12.23). (Of course the narrower the slit the less the light that gets through. This was compensated for by longer exposures.)

Given that light seems to travel in straight lines, can we tell how fast it goes? Galileo discussed this problem in his Dialogues Concerning Two New Sciences. He points out that everyday experiences might lead us to conclude that the propagation of light is instantaneous. But these experiences, when analyzed more closely, really show only that light travels much faster than sound. For example, "when we see a piece of artillery fired, at a great distance, the flash reaches our eyes without lapse of time; but the sound reaches the ear only after a noticeable interval." But how do we really know that the light moved "without lapse of time" unless we have some accurate way of measuring the lapse of time?

Galileo then described an experiment by which the speed of light might be measured by two persons on distant hills flashing lanterns. (This experiment is to be analyzed in SG 13.2). He concluded that the speed of light is probably not infinite, but was not able to estimate a definite value for it.

The first definite evidence that light moves at a finite speed was found by a Danish astronomer, Ole Römer. In September 1676, Römer announced to the Academy of Sciences in Paris that the eclipse of a satellite of Jupiter, which was expected to occur at 45 seconds after 5:25 a.m. on the ninth of November, would be exactly ten minutes late. On November 9, 1676, astronomers at the Royal Observatory in Paris, though skeptical of Römer's mysterious prediction, made careful observations of the eclipse and reported that it occurred at 45 seconds after 5:35 a.m., just as Römer had predicted.

Two weeks later, Römer revealed the theoretical basis of his prediction to the baffled astronomers at the Academy of Sciences. He explained that the delay in the eclipse was simply due to the fact that light from Jupiter takes a longer or shorter time to reach the earth, depending on the relative positions of Jupiter and the earth in their orbits. In fact, he declared that it takes 22 minutes for light to cross the earth's orbit.

[Römer] the sage, who, studious of the skies,
Heedful explores these late-discovered worlds,
By this observed, the rapid progress finds
Of light itself; how swift the headlong ray
Shoots from the Sun's height through unbounded space,
At once enlightening air, and Earth, and Heaven.

David Mallett, The Excursion, eighteenth century.

Shortly thereafter, the Dutch physicist Christiaan Huygens used Römer's data to make the first calculation of the speed of light. He combined the value of 22 minutes for light to cross the earth's orbit with his own estimate of the diameter of the earth's orbit. (This distance could be estimated for the first time in the seventeenth century, as a result of the advances in astronomy described in Unit 2.) Huygens obtained a value which, in modern units, is about 2×10^8 meters per second. This is about two-thirds of the presently accepted value (see below). The discrepancy is mainly due to the fact that light actually takes only about 16 minutes to cross the earth's orbit. As often happens, modern historians of science have cast some doubt on the exactness of Römer's calculation of the time interval and on the observation of the time of the eclipse. Nevertheless, the importance of Römer's work was not so much that it led to a particular value of the speed of light, but rather that it established that the propagation of light is not instantaneous but takes a finite time.

See the article "Velocity of Light" in Project Physics Reader 4.

The speed of light has been measured in many different ways since the seventeenth century. Since the speed is very high, it is necessary to use either a very long distance or a very short time interval. The earlier methods were based on measurements of astronomical distances. In the nineteenth century, rotating slotted wheels and mirrors made it possible to measure very short time intervals so that distances of a few miles could be used. The development of electronic devices in the twentieth century allows measurement of even shorter time intervals, so that the speed of light is now known to an accuracy of better than 1 part in 10^6. Because of the importance of the speed of light in modern physical theories, physicists are continuing to improve their methods of measurement even though this speed is already one of the most accurately known physical constants.

As of 1964, the most accurate measurements indicate that the speed of light in vacuum is 299,792,500 meters per second. The uncertainty of this value is less than 300 meters per second, or 0.0001%. The speed of light is usually represented by the symbol c, and for most purposes it is sufficient to use the approximate value $c = 3 \times 10^8$ meters per second.

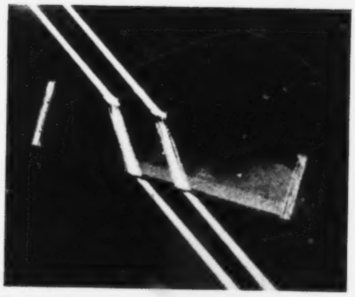
Q1 Why can't a beam of light be made increasingly narrow by passing it through narrower and narrower slits?

Q2 What reason did Römer have for thinking that the eclipse of a particular satellite of Jupiter would be observed later than expected?

Q3 What was the most important outcome of Römer's work?

13.3 Reflection and refraction.

What happens when a ray of light traveling in one medium (say air) hits the boundary of another medium (say glass)? The answers to this question depend on whether we adopt a particle or a wave theory of light, and therefore give us a chance to test which theory is better.



Two narrow beams of light, coming from the upper left, strike a block of glass. Can you account for the other effects?

We have already discussed reflection and refraction from the wave viewpoint in Chapter 12, so we need only recall the results obtained there.

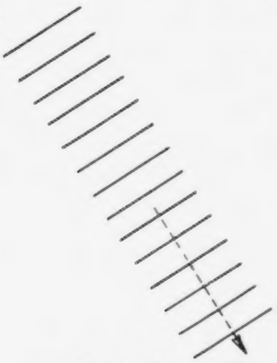
1) A ray may be taken as the line drawn perpendicular to a wave's crest lines; a ray represents the direction in which a train of parallel waves is traveling.

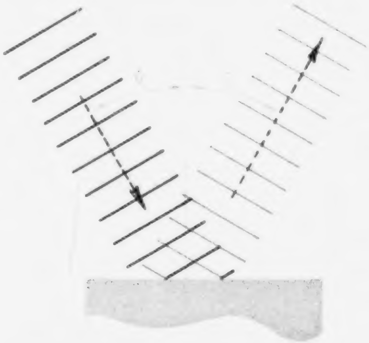
2) In reflection, the angle of incidence (θ_i) is equal to the angle of reflection (θ_r).

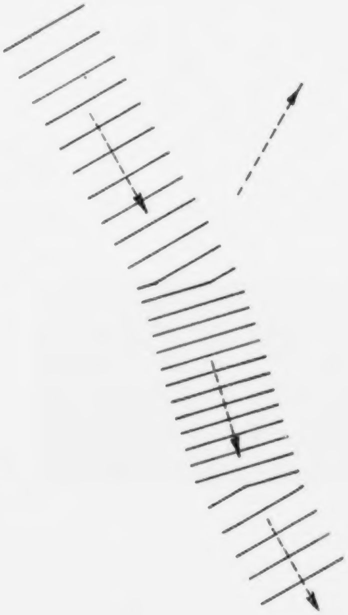
3) Refraction involves a change of wavelength and speed of the wave as it goes into another medium. In particular, when the wavelength decreases, the speed decreases, and the ray is bent in a direction toward a line perpendicular to the boundary. This bending toward the perpendicular is observed when a ray of light goes from air to glass.

SG 13.6
SG 13.7
SG 13.8
SG 13.9
SG 13.10

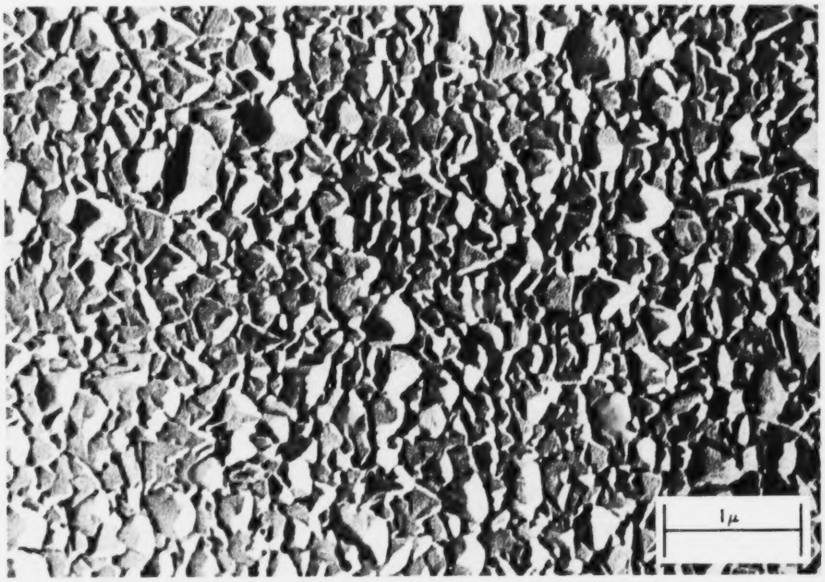
The incident, reflected and refracted rays are in a plane perpendicular to the surface.







What about the particle model? Newton pointed out that reflection could not be simply the result of the impact of light particles against the particles of the reflecting surface. After all, a polished surface is only smooth to the gross sense of human sight and touch. Looked at through a microscope, it shows endless hills and valleys. If particles of light actually hit such a wrinkled surface they would be scattered in all directions. To avoid this consequence, there must be (as Newton put it) "some feature of the body which is evenly diffused over its surface and by which it acts



The surface of a mirror as it appears on an electro micrograph. The surface is a 3μ thick aluminum film prepared by vaporizing aluminum metal in a vacuum chamber. The magnification here is nearly 26,000. (μ stands for micron; where 1μ = 10^{-6} meter)

Newton's particle model: repelling forces would cause reflection, attracting forces would cause refraction.

upon the ray without immediate contact." Obviously, this force or "power" was one which repelled the particles of light. A similar power, which attracted light particles instead of repelling them, could be used to explain refraction. As a particle of light approached a boundary of another medium, it would first have to penetrate the repulsive power; if it did that, it would then meet an attractive power in the medium which would pull it into the medium. Since the attractive force would be a vector with a component in the direction of the original motion of the ray, the light particle's speed would increase. If the ray were moving at an oblique angle to the boundary, its direction would change in the medium toward the line perpendicular to the boundary.

According to the particle model, therefore, we can make the following predictions about reflection and refraction.

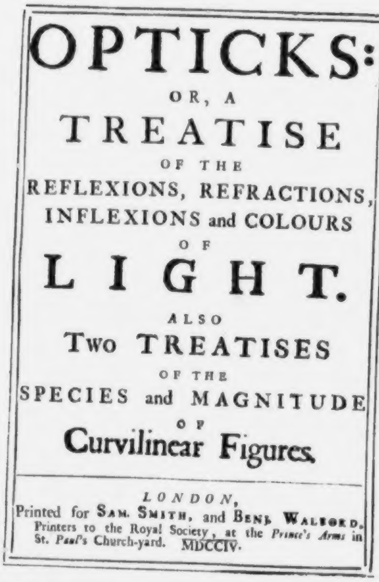
1) A ray represents the direction in which the particles are moving.

SG 13.11
SG 13.12

2) In reflection, the angles of incidence and reflection are equal. This prediction can be derived from the Law of Conservation of Momentum (Chapter 9) applied to the interaction of the particles with the repulsive power of the medium. (See SG 13.12.)

3) Refraction involves a change of speed of the particles as they go into another medium. In particular, when an attractive power acts, the speed increases and the ray is bent into the medium.

Comparing these features of the particle model with the corresponding features of the wave model (above), we see that the only difference is in the relation between speed and refraction of a ray. When we observe that a ray is bent toward the perpendicular on going into another medium—as is the case for light going from air into water—then the particle theory predicts that light has a higher speed in the second medium, whereas the wave theory predicts that light has a lower speed.



OPTICKS:
OR, A
TREATISE
OF THE
REFLEXIONS, REFRACTIONS,
INFLEXIONS and COLOURS
OF
LIGHT.
ALSO
Two TREATISES
OF THE
SPECIES and MAGNITUDE
OF
Curvilinear Figures.

LONDON,
Printed for SAM. SMITH, and BENJ. WALFORD,
Printers to the Royal Society, at the *Prince's Arms* in
St. *Paul's* Church-yard. MDCCIV.

Title page from the first edition of Newton's Opticks, in which he described his particle model.

You might think that it would be fairly easy to devise an experiment to determine which prediction is correct. All one has to do is measure the speed of light in water. However, in the late seventeenth and early eighteenth centuries, when the wave model was supported by Huygens and the particle model by Newton, no such experiment was possible. Remember that at that time the only available way of measuring the speed of light was an astronomical one. Not until the middle of the nineteenth century did Fizeau and Foucault measure the speed of light in water. The results agreed with the predictions of the wave model: the speed of light is lower in water than in air. But by the time these experiments were done, most physicists had already accepted the wave model for other reasons (see below). The Foucault-Fizeau experiments of 1850 were generally regarded as driving the last nail in the coffin of the particle theory.

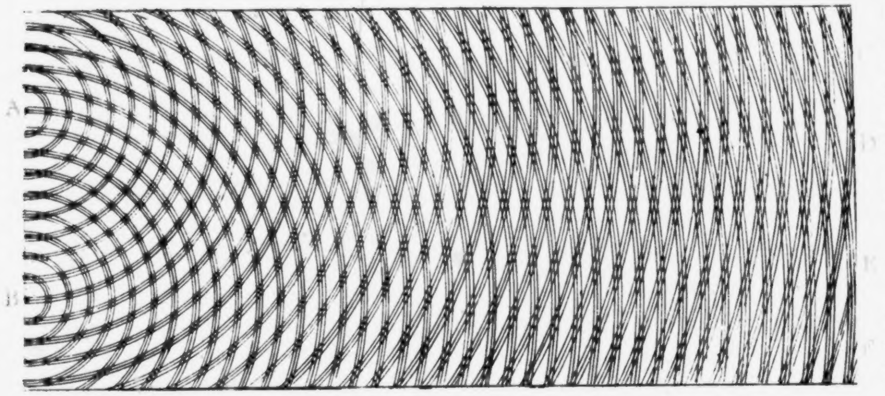
Q4 What evidence showed conclusively that Newton's particle model of refraction was not valid for light?

Q5 If light has a wave nature, what changes take place in the speed, wavelength and frequency of light passing from air into water?

13.4 Interference and diffraction. From the time of Newton until the early years of the nineteenth century, the particle theory of light was favored by most physicists, largely because of the prestige of Newton. Early in the nineteenth century, however, the wave theory was revived by Thomas Young. He found, in experiments made between 1802 and 1804, that light shows the phenomenon of interference. Interference patterns have been discussed in Sec. 12.6 in connection with water waves. Such patterns could not easily be explained by the particle theory of light. Young's famous "double-slit experiment" provided convincing evidence that light has properties that can only be explained in terms of waves.

When a beam of light is split into two beams, and the split beams are then allowed to overlap, we find that the two wave trains interfere constructively in some places and destructively in others. To simplify the interpretation of the experiment, we will assume that the light has a single definite wavelength λ. (Young's original experiment was done with sunlight, which, as Newton had already shown, is a mixture of waves of different wavelengths.)

Thomas Young's original drawing showing interference effects in overlapping waves. Place the eye near the left edge and sight at a grazing angle along the diagram.

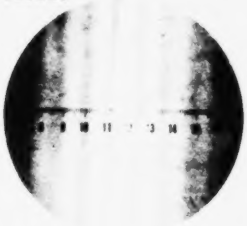


Thomas Young (1773-1829) was an English linguist, physician and expert in many fields of science. At the age of fourteen he was familiar with Latin, Greek, Hebrew, Arabic, Persian, French and Italian, and later was one of the first successful workers at decoding Egyptian hieroglyphic inscriptions. He studied medicine in England, Scotland and Germany. While still in medical school he made original studies of the eye, and later developed the first version of what is now known as the three-color theory of vision. He also did research in physiology on the functions of the heart and arteries, and studied the human voice mechanism, through which he became interested in the physics of sound and sound waves.

Young then turned to optics, and discovered that Newton's experiments with light could be explained in terms of waves. This conclusion was strongly attacked by some scientists in England because of the suggestion that Newton might be wrong.

See Young's paper "Experiments and Calculations Relative to Physical Optics" in Project Physics Reader 4.

Young allowed sunlight to fall on a pinhole punched in a screen. The emerging light from this "source" spread out by diffraction and fell on two pinholes punched near each other (at a distance d apart) in a second screen. Again, diffraction occurred and the hemispherical waves from each pinhole spread out into the space beyond the second screen. The interference pattern can then be seen where the light strikes a third screen. Where interference is constructive, we will get a bright region. Where interference is destructive, we will get a dark region.



A polaroid photograph taken through a Project Physics magnifier placed about 30 cm behind a pair of closely spaced slits. The slits were illuminated with a narrow but bright light source.

By measuring the distance between successive bright lines in the interference pattern, we can calculate the wavelength of the light. The formulas needed for this calculation were derived in Sec. 12.6.

The fact that Young could actually find experimental values for the wavelength of light was additional evidence in favor of the wave theory. Here is his result:

"breadth of the undulations" means the wavelength

> From a comparison of various experiments, it appears that the breadth of the undulations constituting the extreme red light must be supposed to be, in air, about one 36 thousandth of an inch, and those of the extreme violet about one 60 thousandth; the means of the whole spectrum, with respect to the intensity of light, being one 45 thousandth.

SG 13.13
SG 13.14

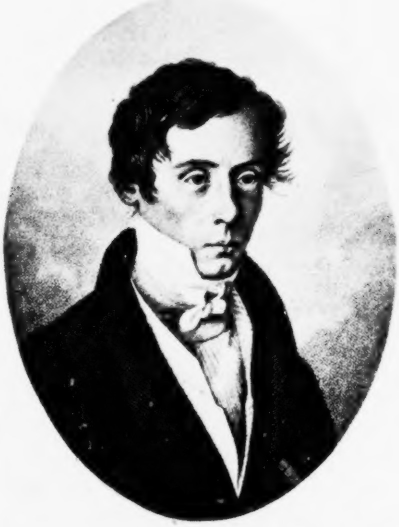
When Young announced his new results supporting the wave theory of light, he took special pains to show that Newton himself had made several statements favoring the wave theory, even though he was generally considered a supporter of the particle theory. Nevertheless, Young was received with ridicule and even hostility by those British scientists to whom Newton's name was sacred. It was not until 1818, when the French physicist Augustin Fresnel proposed a mathematical wave theory of his own, that Young's research got the credit it deserved. Fresnel also had to submit his work for approval to a group of physicists who were already committed to the particle theory. The French physicists, however, thought that the particle theory could be proved correct by mathematics rather than by appealing to the authority of an English scientist (Newton). One of them, the brilliant mathematician Simon Poisson, took Fresnel's wave equations and showed that if these equations really did describe the behavior of light, a very peculiar thing ought to happen when a small disk is placed in a beam of light. A screen placed behind the disk should have a bright spot in the center of the shadow, because diffraction of the light waves around the edge of the disk should lead to constructive interference at the center. According to the particle theory, there could be no such

Henry Brougham, a British politician and amateur scientist, wrote in the Edinburgh Review in 1803: "this paper [by Young] contains nothing which deserves the name, either of experiment or discovery, and ... is in fact destitute of every species of merit ...We wish to raise our feeble voice against innovations, that can have no other effect than to check the progress of science, and renew all those wild phantoms of the imagination which Bacon and Newton put to flight from her temple."

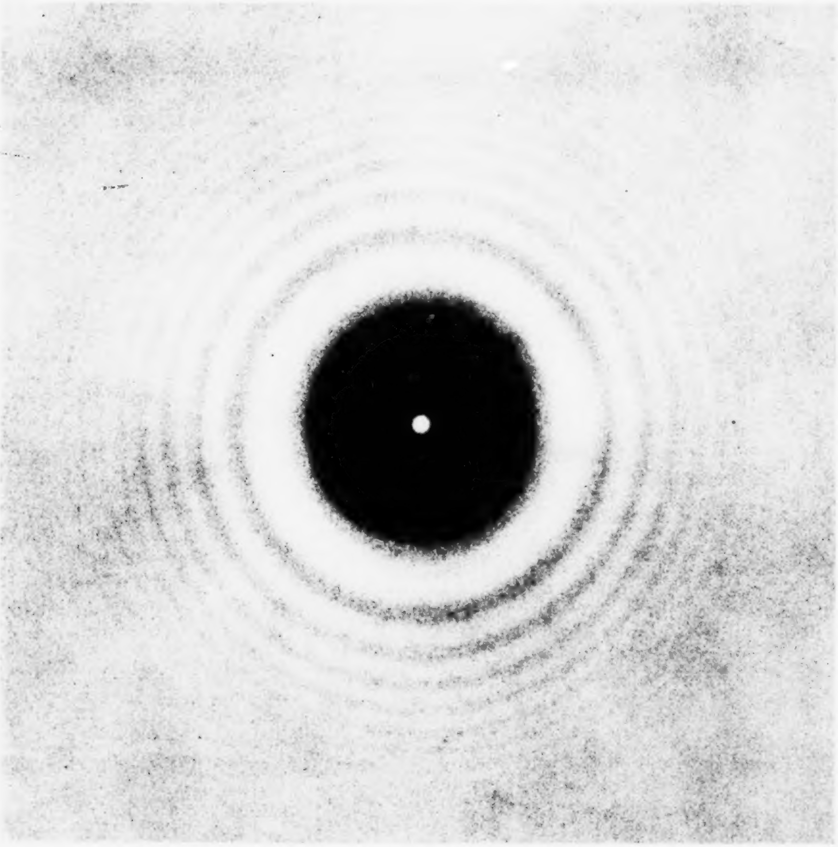
SG 13.15

bright spot. Since such a bright spot had never been observed, and furthermore the idea of a bright spot in the center of a shadow was absurd, Poisson announced gleefully to Fresnel that he had refuted the wave theory.

Fresnel accepted the challenge and arranged for this prediction to be tested by experiment immediately. The result: there was a bright spot in the center of the shadow, as predicted by Poisson on the basis of Fresnel's wave theory.



Augustin Jean Fresnel (1788-1827) was an engineer of bridges and roads for the French government. In his spare time he carried out extensive experimental and theoretical work in optics. Fresnel developed a comprehensive wave model of light that successfully accounted for reflection, refraction, interference and polarization. He also designed a lens system for lighthouses that is still used today.



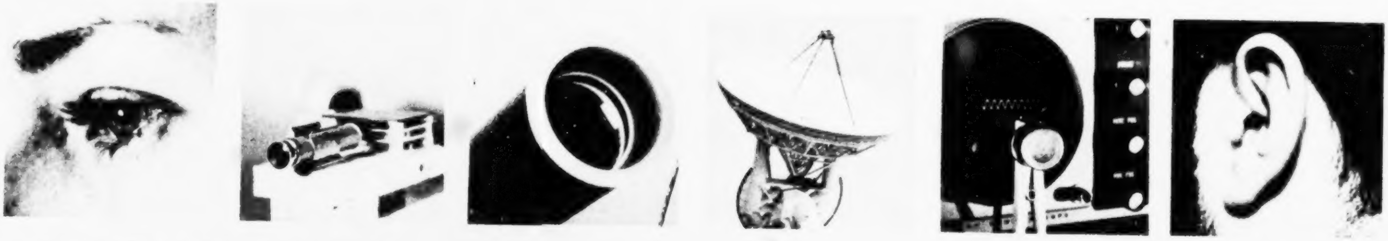
Diffraction pattern due to an opaque circular disc showing the Poisson bright spot in the center of the shadow. Note also the bright and dark fringes of constructive and destructive interference.

As soon as the significance of the Young double-slit experiment and the Poisson bright spot was realized, support for the particle theory of light began to crumble away. By 1850 the validity of the wave model was generally accepted, and physicists began to concentrate on working out the mathematical consequences of this model and its application to all the different properties of light.

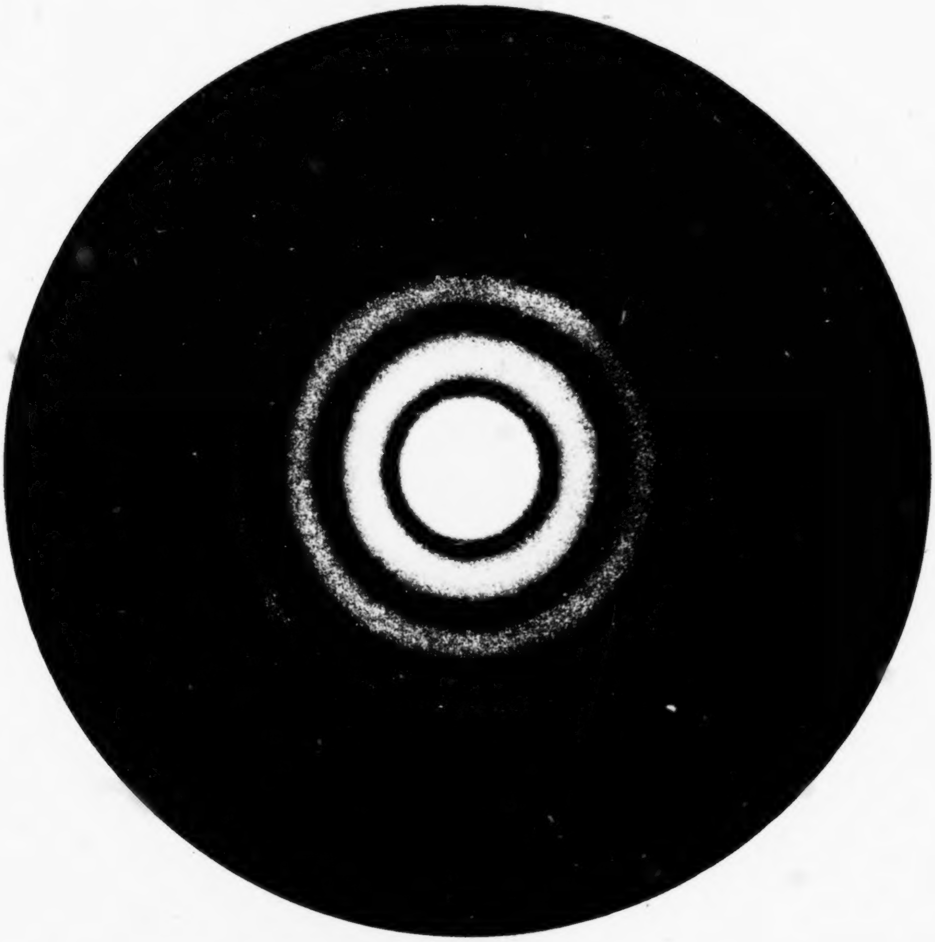
Q6 How did Young's experiments support the wave model of light?

Q7 In what way is diffraction involved in Young's experiments?

Q8 What remarkable phenomenon was shown by Poisson to be predictable on the basis of Fresnel's wave theory?

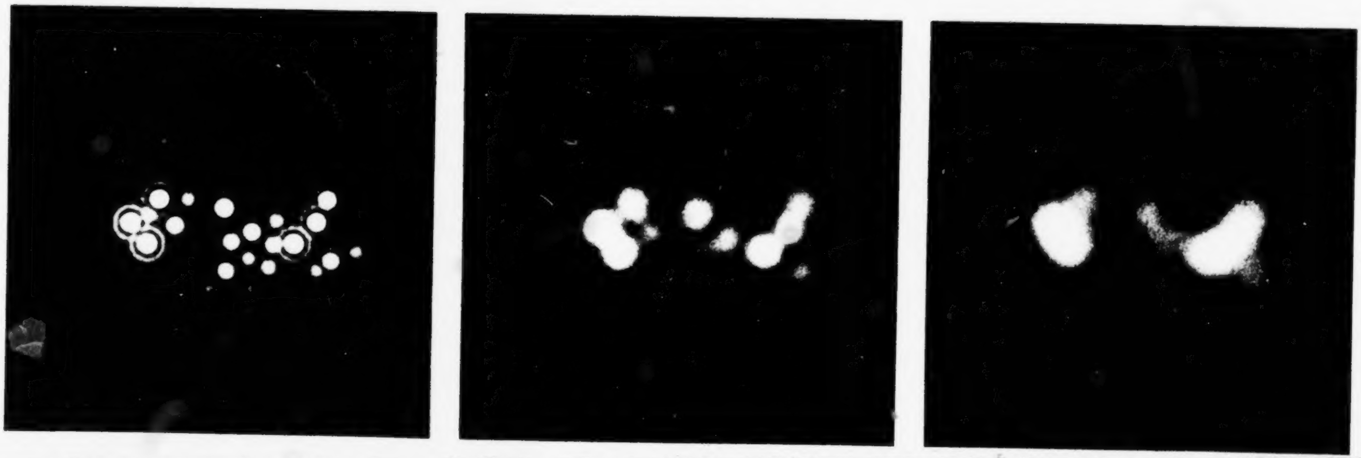


Loss of Detail Through Diffraction



The photograph on the left shows the diffraction image of a point source of light. Diffraction by the camera lens opening has spread the light energy into a bright central disc surrounded by alternate dark and bright rings. The photographs below show an array of point sources, recorded through a progressively smaller and smaller hole. The array could represent a star cluster, surface detail on mars, granules in living cells or simply specific points on some object.

We obtain most of the information about our environment by means of waves (light, sound, radio, etc.) which we receive through a hole; the pupil of the eye, the entrance to the ear, the aperture of an optical telescope or radio telescope, etc. The diffraction of the waves from the edges of the hole limits the detail of information that it is possible to receive. As the hole through which we observe the array on the left becomes smaller, the diffraction image of each point spreads out and begins overlapping the diffraction images of other points. When the diffraction patterns for the points overlap sufficiently it is impossible to distinguish between them.



13.5 Color. Early man's appreciation of color survives for our contemplation in the coloring agents found in prehistoric painting, pottery and fabrics. But no scientific theory of color was developed before the time of Newton. Until then, most of the commonly accepted ideas about color had been advanced by artist-scientists, like da Vinci, who based their ideas on experiences with mixing pigments. Even today, a child's first knowledge of colors usually comes from the paint box.

Unfortunately, the lessons learned in mixing pigment can rarely be applied to the mixing of colors of light. In early times, it was thought that white light from the sun was "pure light," and that—as by refraction in glass—color came from adding impurity to this pure light.

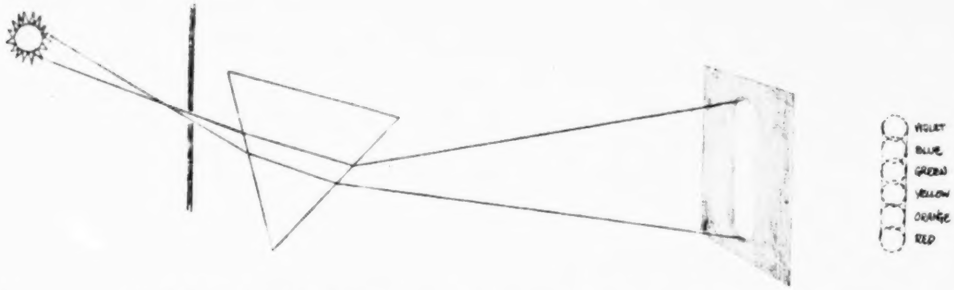
Newton became interested in colors while he was still a student at Cambridge University, when he set out to construct an astronomical telescope. One of the troublesome defects of the telescope was a fuzzy colored edge that always surrounded the image formed by the telescope lens. It was perhaps in an attempt to understand this particular defect that he began his extensive study of color.

In 1672, at the age of 29, Newton published a theory of the nature of color in the Philosophical Transactions of The Royal Society of London. This was his first published scientific paper, and it is an outstanding example of scientific reporting. He wrote:

> ...in the beginning of the year 1666 (at which time I applied myself to the grinding of optic glasses of other figures than spherical) I procured me a triangular glass prism, to try therewith the celebrated phenomena of colors. And in order thereto having darkened my chamber and made a small [round] hole in my window shuts, to let in a convenient quantity of the sun's light, I placed my prism at this entrance, that it might thereby be refracted to the opposite wall. It was at first a pleasing divertissement to view the vivid and intense colours produced thereby....

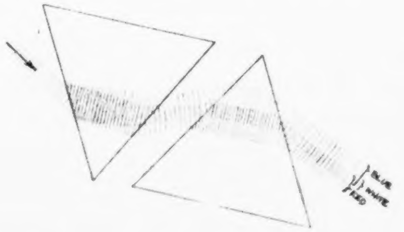
The cylindrical beam of white light from the circular opening passed through the prism and produced on the opposite wall an elongated patch of colored light which was violet at one end, red at the other and showed a continuous gradation of colors in between. For such a pattern of colors, Newton invented the name spectrum.

But, Newton asked himself, from where do the colors come, and why is the image spread out in an elongated patch rather than circular? Seeking an explanation, Newton passed the light through different thicknesses of the glass, changed the size of the hole in the window, and even placed the prism



This drawing is similar to Newton's diagram of the refraction of white light by a prism. Instead of the image of the sun being circular, it was an oblong patch of colored light having straight parallel sides and semi-circular and rather fuzzy ends.

outside the window. But he found that none of these changes in conditions had any effect on the spectrum. To test whether some unevenness or irregularity in the glass produced the spectrum, he passed the colored rays from one prism through a second prism turned upside down. If some irregularity in the glass was responsible for spreading out the beam of light, then passing this beam through the second prism should spread it out even more. Instead, the second prism, when properly placed, served to bring the colors back together to form a spot of white light, as if the light had not passed through either prism.



As is suggested in the diagram, the recombination of colors is not complete. Newton himself noted:

"The prisms also must be placed very near to one another; for if their distance be so great, the colours begin to appear in the light, before its incidence on the second prism, these colours will not be destroyed by the contrary refractions of that prism."

By such a process of elimination, Newton convinced himself of a belief that he probably had held from the beginning: white light is composed of colors. It is not the prism that manufactures the colors; they were there all the time, but mixed up so that they could not be distinguished. When white light passes through a prism, each of the component colors is refracted at a different angle, so that the beam is spread into a spectrum.

As a further test of his hypothesis, Newton cut a small hole in a screen on which a spectrum was projected, so that light of a single color could be separated out and passed through another prism. He found that the second prism had no further effect on this single-color beam, aside from refracting it again. Once the first prism had done its job of separating out the colored components of white light, the second prism could not change the color of the components.

Summarizing his conclusions, Newton wrote:

> Colors are not Qualifications of Light derived from Refraction or Reflection of natural Bodies (as 'tis generally believed) but Original and Connate Properties, which in divers Rays are divers. Some Rays are disposed to exhibit a Red Colour and no other; some a Yellow and no other, some a Green and no

> other, and so of the rest. Nor are there only Rays proper and particular to the more Eminent Colours, but even to all their intermediate gradations.

Apparent colors of objects. So far Newton had discussed only the colors of rays of light, but in a later section of his paper he raised the important question: why do objects appear to have certain colors? Why is the sky blue, the grass green, a paint-pigment yellow or red? Newton proposed a very simple answer:

> That the Colours of all Natural Bodies have no other Origin than this, that they...Reflect one sort of Light in greater plenty than another.

In other words, a red pigment looks red to us because when white sunlight falls on it, the pigment absorbs most of the rays of other colors of the spectrum and reflects mainly the red to our eyes.

According to Newton's theory, color is not an inherent property of an object itself, but depends on how the object reflects and absorbs the various colored rays that strike it. Newton justified this hypothesis by pointing out that an object may appear to have a different color when a different kind of light shines on it. For example, if we shine blue light on a pigment that usually appears red, the pigment will reflect a little of the blue light, and since there is no red for it to reflect, it will appear blue. Newton wrote:

> I have experimented in a dark Room, by illuminating those Bodies with uncompounded [pure] light of divers Colours. For by that means any Body may be made to appear of any Colour. They have therefore no appropriate Colour, but ever appear of the Colour of the Light cast upon them, but yet with this different, that they are most brisk and vivid in the Light of their own Day-light Colour.

Nowadays it is a familiar observation that clothing of certain colors appears different under artificial light and in sunlight.

Reactions to Newton's theory. Newton's theory of color met with violent opposition at first. Other British scientists, especially Robert Hooke, objected that postulating a different kind of light for each color was unnecessary. It would be simpler to assume that the different colors were produced from pure white light by some kind of modification. Hooke, for example, proposed a color theory based on the wave model of light: ordinarily, in white light, the wave front is perpendicular to the direction of motion. (See Sec. 12.5 for a definition of wave front.) Colors are produced, according to Hooke, when refraction by another medium twists the wave front so that it is no longer perpendicular to the direction of motion.

Newton was aware of the fallacies in Hooke's theory, but he disliked controversy and did not attack it publicly. In fact, he waited until after Hooke's death in 1703 to publish his own book, Opticks (1704), in which he reviewed the properties of light and matter.

Although Newton's Principia was a much more important work from a scientific viewpoint, his Opticks had considerable influence on the literary world. English poets, celebrating the discoveries of their country's greatest scientist, were dimly aware of the significance of Newton's theory of gravity, but could not grasp the technical details of the geometric axioms and proofs of the Principia. But Newton's spectrum of colors provided ample opportunity for poetic fancy:

> ...First the flaming red,
> Springs vivid forth; the tawny orange next;
> And next delicious yellow; by whose side
> Fell the kind beams of all-refreshing green.
> Then the pure blue, that swells autumnal skies,
> Ethereal played; and then, of sadder hue,
> Emerged the deepened indigo, as when
> The heavy-skirted evening droops with frost;
> While the last gleamings of refracted light
> Died in the fainting violet away.
> [James Thomson, "To the Memory of Sir Isaac Newton" (1727).]

Newton's ideas are also evident in a poem on the rainbow:

> Meantime, refracted from yon eastern cloud,
> Bestriding earth, the grand ethereal bow
> Shoots up immense; and every hue unfolds,
> In fair proportion running from the red
> To where the violet fades into the sky.
>
> Here, aw[e]ful Newton, the dissolving clouds
> Form, fronting on the sun, thy showery prism;
> And to the sage-instructed eye unfold
> The various twine of light, by thee disclosed
> From the white mingling blaze.
> [James Thomson, "Spring" (1728).]

Leaders of the nineteenth-century Romantic movement in literature, and the German "nature philosophers," did not think so highly of Newton's theory of color. The scientific procedure of dissecting and analyzing natural phenomena by experiments was distasteful to them. They preferred to speculate about the unifying principles of all natural forces, in order to grasp nature as a whole. The German philosopher Friedrich Schelling wrote in 1802:

> Newton's Opticks is the greatest illustration of a whole structure of fallacies which, in all its parts, is founded on observation and experiment.

The foremost German poet, Goethe, spent many years trying to overthrow Newton's theory of colors, both by his own experiments and by impassioned arguments. Goethe insisted on the purity of white light in its natural state. To the nineteenth-century physicists who were trying to use Newton's theory to explain newly-discovered color phenomena, he addressed the following poem:

> May ye chop the light in pieces
> Till it hue on hue releases;
> May ye other pranks deliver,
> Polarize the tiny sliver
> Till the listener, overtaken,
> Feels his senses numbed and shaken—
> Nay, persuade us shall ye never
> Nor aside us shoulder ever.
> Steadfast was our dedication—
> We shall win the consummation.

Goethe rejected Newton's hypothesis that white light is a mixture of colors, and suggested that colors are produced by the interaction of white light and its opposite (or absence), darkness. Although Goethe's experiments on the perception of color were of some value to science, his theory of the physical nature of color did not survive the criticism of physicists. Newton's theory of color was firmly established, even in literature. SG 13.16

Q9 How did Newton show that white light was not "pure"?

Q10 Why could Newton be confident that green light was not itself composed of different colors of light?

Q11 How would Newton explain the color of a yellow coat?

Q12 Why was Newton's theory of color attacked by the nature philosophers ?

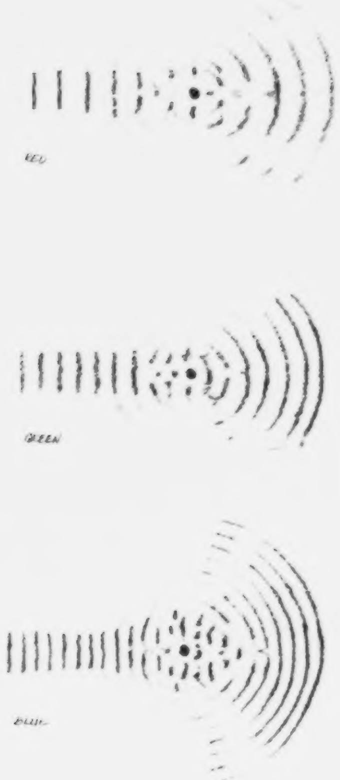
13.6 Why is the sky blue? As Newton suggested, the apparent colors of natural objects depend on which color is predominantly reflected by the object. But in general, there is no simple way of predicting what colors an object will reflect. This is a difficult problem, involving the physical and chemical properties of the object. However, the color of the sky can be explained fairly simply if we introduce just one more fact about color: the relation between color and wavelength.

As Thomas Young found in his two-slit experiment (Sec. 13.4), different colors have different wavelengths. To specify the wavelength of light a special unit is used—the Ångstrom (Å), equal to 10^{-10} meter. The range of the visible spectrum is from about 7000 Å for red light to about 4000 Å for violet light.

The Ångstrom is named after Anders Jonas Ångstrom, a Swedish astronomer who, in 1862, used spectroscopic techniques to detect the presence of hydrogen in the sun.

Newton found that rays of different colors are refracted by different amounts as they go through a glass prism. Since we know that waves are refracted when they go into a medium in which their speed is different, we can conclude that the speed of light in glass depends on its wavelength.

The scattering of waves by small obstacles also depends on wavelength. This fact can be demonstrated by experiments with waves in a ripple tank. As a general rule, the longer a wave is compared to the size of the obstacle, the less it is scattered by the obstacle. For light, calculations show that the amount of scattering decreases as the fourth power of the wavelength. This means that, since the wavelength of red light is almost twice the wavelength of blue light, the scattering of red light is only a little more than 1/16th as much as the scattering of blue light.



The scattering of different colors by a tiny obstacle is shown here for wavelengths representing red, green and blue light.

Now we can explain why the sky is blue. Light from the sun is scattered by air molecules and particles of dust or water vapor in the sky. Since these particles are usually much smaller than the wavelength of any kind of visible light, we can apply the general rule mentioned above, and conclude that light of shorter wavelengths (blue light) will be much more strongly scattered from the particles than light of longer wavelengths. The rays of longer wavelength (such as red) are not scattered very much, and they reach our eyes only when we look directly at the sun—but then they are mixed with all the other colors.

An observer looking at a sunset is receiving primarily unscattered colors such as red; whereas if the observer looks overhead he will be receiving primarily scattered colors, the most dominant of which is blue.

If the earth had no atmosphere, the sky would appear black and stars would be visible by day. In fact, starting at altitudes of about ten miles, where the atmosphere becomes quite thin, the sky does look black and stars can be seen during the day; this has been confirmed by reports and photographs brought back by astronauts.

When the air contains dust particles or water droplets as large as the wavelength of visible light (about 10^{-6} meter), other colors than blue may be strongly scattered. For example, the quality of sky coloring changes with the water-vapor content of the atmosphere. On clear, dry days the sky is a much deeper blue than on clear days with high humidity. The intensely blue skies of Italy and Greece, which have been an inspiration to poets and painters for centuries, are a result of the drier air over these countries.

Unusual events that change atmospheric conditions can produce strange color effects. On August 27, 1883, the volcano Krakatau (on an island between Sumatra and Java) exploded, making a hole 1,000 feet deep. The explosion was heard 2,500 miles away, and created ocean waves which killed 35,000 people. For months afterwards, as a layer of fine volcanic dust spread through the earth's atmosphere, the world witnessed a series of unusually beautiful sunrises and sunsets.

The following quotation is from a letter written by Vincent Van Gogh and refers to Arles in Southern France:

> ...,nature here being so extraordinarily beautiful. Everywhere and all over the vault of heaven is a marvellous blue, and the sun sheds a radiance of pale sulphur, ...it absorbs me so much that I let myself go, never thinking of a single rule.

Q13 **How does the scattering of light waves by tiny obstacles depend on the wavelength?**

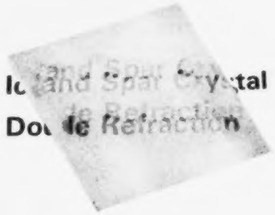
Q14 **How would you explain the blue color of the sky?**

13.7 Polarization. How could Newton, who made major discoveries in optics as well as in many other areas of physics, have refused to accept the wave model for light? Actually Newton did not reject the wave theory. He even suggested that different colored rays of light might have different wavelengths, and used this idea to explain the colors observed in thin plates and bubbles. But Newton could not accept the proposal of Hooke and Huygens that light is just like sound —that is, that light is nothing but a spherical pressure-wave propagated through a medium. Newton argued that light must also have some particle-like properties.

Newton mentioned two properties of light which, he thought, could not be explained without attributing particle properties to light. First, light is propagated in straight lines, whereas waves spread out in all directions and go around corners. The answer to this objection could not be given until early in the nineteenth century, when Young was able to measure the wavelength of light and found that it is much smaller than Newton had supposed. Even red light, which has the longest wavelength of any part of the visible spectrum, has a wavelength less than a thousandth of a millimeter. As long as light only shines on or through objects of ordinary size —a few centimeters in width, say—light will appear to travel in straight lines. Diffraction and scattering effects don't become evident until a wave strikes an object whose size is similar to its own wavelength.

Iceland Spar Crystal
Double Refraction

Newton's second objection was based on the phenomenon of "polarization" of light. In 1669, the Danish scientist Erasmus Bartholinus discovered that crystals of Iceland spar had the curious property of splitting a ray of light into two rays. Thus small objects viewed through the crystal looked double. Huygens discussed the "double refraction" of light by Iceland spar in his treatise on light, but could not explain it satisfactorily with his



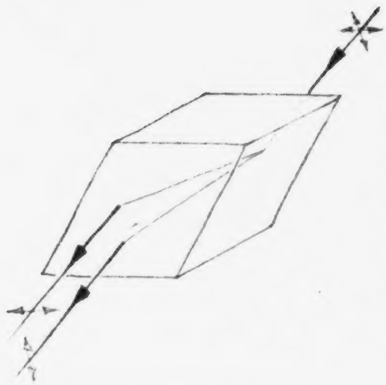
wave model. However, he did find that one of the rays refracted by the crystal can be split again if it strikes another crystal of Iceland spar, but is not split for certain orientations of the second crystal.

To Newton it was clear that this behavior could only be explained by assuming that the ray is "polarized." That is, the ray has "sides" so that its properties depend on its orientation around its axis. This would be easy enough to understand if the ray is a stream of rectangular particles, but rather mysterious if light is a wave motion. As Newton pointed out,

> For Pressions or Motions, propagated from a shining Body through a uniform Medium, must be on all sides alike; whereas by those Experiments it appears, that the Rays of Light have different Properties in their different sides.
>
> [Newton, Opticks, Query 28.]

The answer to this second objection to the wave model for light also had to wait until the beginning of the nineteenth century. Before then, scientists had generally assumed that light waves, like sound waves, must be longitudinal. But around 1820, Young and Fresnel showed that light waves are probably transverse. Their successful explanation of polarization was the major piece of evidence for this conclusion.

In Chapter 12, we stated that in a transverse wave, the motion of the medium itself is always perpendicular to the direction of propagation of the wave. That does not mean that the motion of the medium is always in the same direction; it could be along any line in the plane perpendicular to the direction of propagation. However, if the motion of the medium is predominantly in one direction, for example, vertical, we say that the wave is polarized. (Thus a polarized wave is really the simplest kind of wave; an unpolarized wave is a more complicated thing, since it is a mixture of various motions.)



Double refraction by a crystal of Iceland spar. The incident light is termed "unpolarized," but in effect consists of equal intensities of vertically and horizontally polarized light. The crystal separates these two components, transmitting them through the crystal in different directions and with different speeds.

In 1808, Etienne Malus, a French scientist, noticed that when sunlight reflected from a window passed through a crystal of Iceland spar, only one ray of light came through instead of two. It is now known that light can be polarized by oblique reflection; the reflecting surface absorbs waves that vibrate in one direction and reflects those that vibrate in the others.

Scientific studies of polarization continued throughout the nineteenth century, but practical applications were frustrated because polarizing substances like Iceland spar were scarce and fragile. One of the best polarizers was "herapathite," or sulfate of iodo-quinine, a synthetic crystalline material which transmits polarized light of all colors with almost no absorption. The needle-like crystals of herapathite absorb only light which is vibrating in the direction of the long axis. Herapathite was discovered by an English physician, William Herapath, in 1852, but the crystals were so fragile that there seemed to be no way of using them.

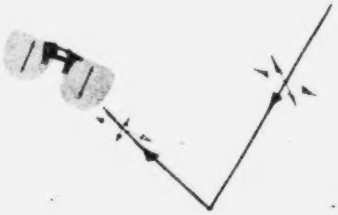
The bee's eyes are sensitive to the polarization of daylight, enabling a bee to navigate by the sun, even when the sun is low on the horizon or obscured. Following the bee's example, engineers have equipped airplanes with polarization indicators for use in arctic regions.

In 1928, Edwin H. Land, a student at Harvard, invented a polarizing plastic sheet he called "Polaroid." His first polarizer consisted of a plastic film in which many microscopic crystals of herapathite are imbedded. The crystals are needle-shaped, and when the plastic is stretched they line up in one direction, so that they all polarize light in the same way. Later, Land improved Polaroid by using polymeric molecules composed mainly of iodine in place of the herapathite crystals.

The properties of Polaroid are easily demonstrated. Hold the lens of a pair of Polaroid sunglasses in front of one eye and look at a shiny surface or light from the blue sky. Rotate the lens. You will notice that, as you do so, the light alternately brightens and dims; you must rotate the lens through an angle of 90° to go from maximum brightness to maximum dimness.

See "Popular Applications of Polarized Light" in Project Physics Reader 4.

How does the polarizer work? If the light that strikes the lens is polarized mainly in one direction, and if this direction happens to coincide with the direction of the long molecules, then the wave will be absorbed because it will set up vibrations within the molecules, and lose most of its energy in this way. However, if the wave is polarized mainly in a direction perpendicular to the direction of the molecules, it will go through the lens without much absorption. If the light that strikes the lens is originally unpolarized —that is, a mixture of waves polarized in various directions —then the lens will transmit those waves that are polarized in one direction, and absorb the rest, so that the transmitted wave will be polarized.



The clip-on sunglasses shown have polarizing lenses that transmit only vertically polarized light. The light reaching the lenses consists of both "unpolarized" diffuse light and horizontally polarized glare. The lenses block the glare and the horizontal component of the diffuse light.

Interference and diffraction effects seem to require a wave model for light. To explain polarization phenomena, the model has to be based on transverse waves. Thus we conclude that the model for light which best explains the characteristics of light considered so far is one which pictures light as a transverse wave motion.

Q15 What two objections did Newton have to a wave model of light?

Q16 What is "unpolarized" light?

13.8 The ether. One thing seems to be missing from the wave model for light. In Chapter 12, we assumed that waves are a special kind of motion that propagates in some substance or "medium," such as a rope or water. What is the medium for the propagation of light waves?

Is air the medium for light waves? No, because light can pass through airless space—for example, the space between the sun and the earth. Even before it was definitely known that there is no air between the sun and the earth, Robert Boyle had tried the experiment of pumping almost all of the air out of a glass container, and found that objects inside remained visible.

"Ether" was originally the name for Aristotle's fifth element, the pure transparent fluid that filled the heavenly spheres; it was later called "quintessence" by scientists in the Middle Ages (see Sections 2.1 and 6.4).

In Newtonian physics it is impossible to imagine motion without specifying what is moving. Scientists therefore invented a hypothetical medium for the propagation of light waves. This medium was called the ether.

In the seventeenth and eighteenth centuries the ether was imagined as an invisible fluid of very low density, which could penetrate all matter and fill all space. It might somehow be associated with the "effluvium"—something that "flows out"—that was used to explain magnetic and electric forces. Early in the nineteenth century, however, Young and Fresnel showed that light waves must be transverse in order to explain polarization. But the only kind of transverse waves known to Young and Fresnel were waves in a solid medium. A liquid or a gas cannot transmit transverse waves, for the same reason that you cannot "twist" a liquid or a gas.

In order to transmit transverse waves, the medium must have some tendency to return to its original shape when it has been deformed. As Thomas Young remarked, "This hypothesis of Mr. Fresnel is at least very ingenious, and may lead us to some satisfactory computations; but it is attended by one circumstance which is perfectly appalling in its consequences ... It is only to solids that such a lateral resistance has ever been attributed: so that ... it might be inferred that the luminiferous ether, pervading all space, and penetrating almost all substances, is not only highly elastic, but absolutely solid!!!"

Since light waves are transverse, and only a solid medium can transmit transverse waves, nineteenth-century physicists assumed that the ether must be a solid. Furthermore, it must be a very stiff solid, because the speed of propagation is very high, compared to other kinds of waves such as sound. Alternatively it might have a very low density; as was stated in Chapter 12, the speed of propagation increases with the stiffness of the medium, and decreases with its density.

But it is absurd to say that a stiff solid ether fills all space, because we know that the planets move through space in accordance with Newton's laws, just as if they were going through a vacuum, with no resistance at all. And of course we ourselves feel no resistance when we move around in a space that transmits light freely.

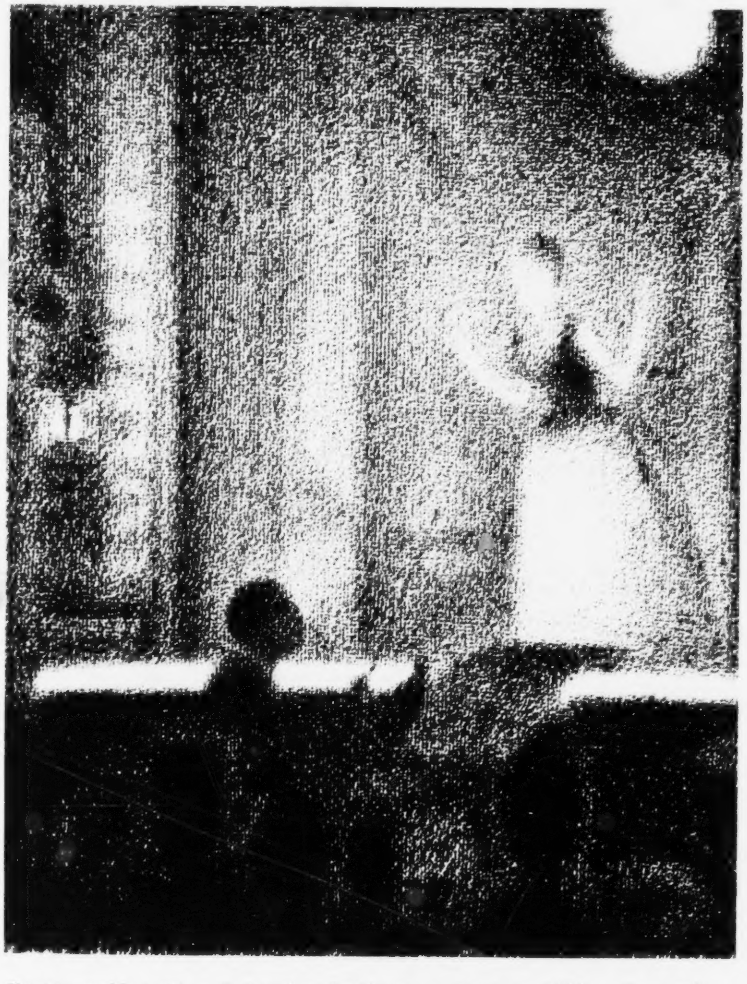
For the moment we must leave the ether as an unsolved problem, just as it was for Newton and the poet Richard Glover who wrote, shortly after Newton's death:

O had great Newton, as he found the cause
By which sound rouls thro' th'undulating air,
O had he, baffling time's resistless power,
Discover'd what that subtile spirit is,
Or whatsoe'er diffusive else is spread
Over the wide-extended universe,
Which causes bodies to reflect the light,
And from their straight direction to divert
The rapid beams, that through their surface pierce,
But since embrac'd by th'icy arms of age,
And his quick thought by times cold hand congeal'd,
Ev'n NEWTON left unknown this hidden power...

[Richard Glover, "A Poem on Newton."]

Q17 **Why was it assumed that an "ether" existed which transmitted light waves?**

Q18 **What remarkable property must the ether have if it is to be the mechanical medium for the propagation of light?**



"Music Hall Artist," drawing by Georges Seurat, 1888. Seurat's use of texture suggests not only the objects and people but also the space between them.

13.1 A square card 3 cm on a side is held 10 cm from a small penlight bulb, and its shadow falls on a wall 15 cm behind the card. What is the size of the shadow on the wall? (A diagram might be useful.)

13.2 An experiment devised by Galileo to determine whether or not the propagation of light is instantaneous is described by him as follows:

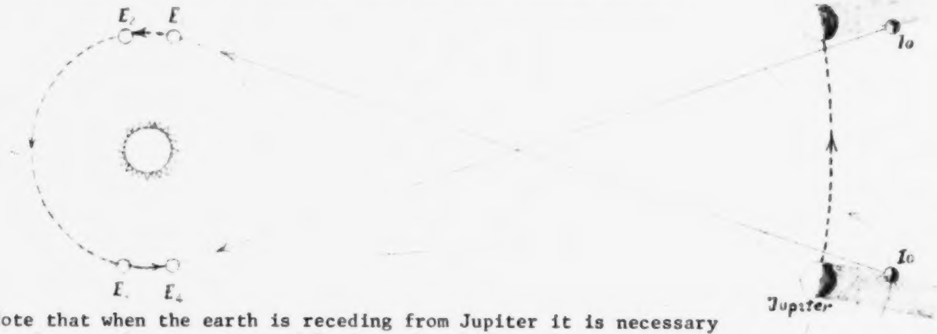
> Let each of two persons take a light contained in a lantern, or other receptacle, such that by the interposition of the hand, the one can shut off or admit the light to the vision of the other. Next let them stand opposite each other at a distance of a few cubits and practice until they acquire such skill in uncovering and occulting their lights that the instant one sees the light of his companion he will uncover his own. After a few trials the response will be so prompt that without sensible error (svario) the uncovering of one light is immediately followed by the uncovering of the other, so that as soon as one exposes his light he will instantly see that of the other. Having acquired skill at this short distance let the two experimenters, equipped as before take up positions separated by a distance of two or three miles and let them perform the same experiment at night, noting carefully whether the exposures and occultations occur in the same manner as at short distances; if they do, we may safely conclude that the propagation of light is instantaneous; but if time is required at a distance of three miles which, considering the going of one light and the coming of the other, really amounts to six, then the delay ought to be easily observable....

But he later states:

> In fact I have tried the experiment only at a short distance, less than a mile, from which I have not been able to ascertain with certainty whether the appearance of the opposite light was instantaneous or not; but if not instantaneous it is extraordinarily rapid....

a) Why was Galileo unsuccessful in the above experiment?
b) Could Galileo have been successful if he had altered his experiment in some reasonable way?
c) Why do you suppose that the first proof of the finite speed of light was based on celestial observations rather than terrestrial observations?
d) What do you think is the longest time that light might have taken in getting from one observer to the other without the observers detecting the delay? Use this estimate to arrive at a lower limit for the speed of light that is consistent with Galileo's description of the result. Was Galileo's experiment completely unsuccessful?

13.3 Römer's prediction described in Sec. 13.2 was based on the natural "clock" provided by the revolution of Io, the second satellite of Jupiter. During each revolution Io passes through Jupiter's shadow, the average time interval between successive immersions into the shadow (or between successive emergences from the shadow) is the period of revolution of Io. Römer used over 70 observations made by himself and the French astronomer Picard to calculate the period to be 42 hr, 28 min, 33 sec. He discovered that all values of the apparent period measured while the earth was receding from Jupiter were greater than the average period he had calculated, and all values measured while the earth was approaching Jupiter were less than the average period. Römer could explain these deviations by assuming that light has a finite speed. Deviations would then be a result of the changes in the distance of the earth from Jupiter which occurred while the period was being measured. The time required for light to travel this change in distance was the deviation observed. For example, if during one revolution of Io the earth moved from E_1 to E_2 as shown in the accompanying diagram, the apparent period would be greater than the average period, whereas if the earth moved from E_3 to E_4, it would be less than the average period.



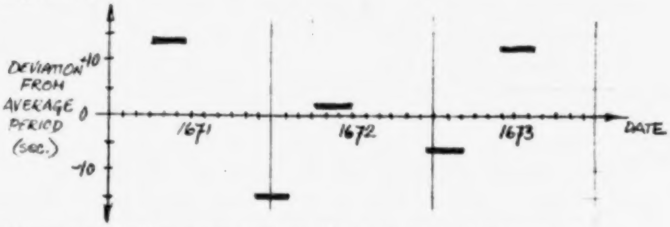
Note that when the earth is receding from Jupiter it is necessary to observe the emergences of Io from the shadow, whereas when the earth is approaching Jupiter, it is necessary to observe the immersions of Io into the shadow.

In the following questions assume that the radius of the earth's orbit is 1.5×10^{11} meters.

a) How far does the earth travel along its orbit during one revolution of Io? (Note that the period of Io is 1 3/4 days.)

b) If the greatest deviation observed for Io's period is very close to 15 seconds, calculate the speed of light. Ignore the very small difference between the chord and the arc of the earth's orbit with which you are concerned. Also ignore the orbital motion of Jupiter which occurs during the measurement of the period of Io.

c) Römer's actual data have been grouped for convenience and five successive groups are shown below plotted against the apparent deviation for those groups (each group consists of several values of the period which were measured during a two- or three-month interval). The positive deviations are for the earth receding from Jupiter and the negative deviations are for the earth approaching Jupiter.

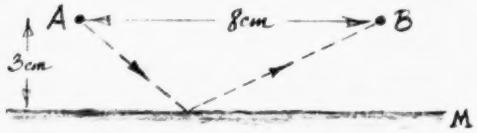


After carefully considering the meaning of the graph, sketch in the curve that best fits the given points. Examine the regularity of the curve; what time interval is required for the curve to complete one cycle and start repeating the pattern again? Can you explain the observed regularity and cyclical nature of the curve?

13.4 A convenient unit for measuring astronomical distances is the light year, defined to be the distance that light travels in one year. Calculate the number of meters in a light year to two significant figures.

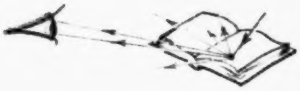
13.5 What time would be required for a spaceship having a speed of 1/1000 that of light to travel the 4.3 light years from the earth to the closest known star other than the sun, Proxima Centauri? Compare the speed given for the spaceship with the speed of approximately 11 km/sec that a rocket from the earth to Venus must have when leaving the earth's atmosphere.

13.6 Find the path from point A to any point on mirror M and then to point B that has the shortest overall length (solve this by trial and error, perhaps by experimenting with a short piece of string held at one end by a tack at point A). Notice that the shortest distance between A, M and B is also the least-time path for a particle traveling at a constant speed from A to M to B. A possible path is shown but it is not necessarily the shortest one. What path would light take from A to M to B?



13.7 What is the shortest mirror in which a 6-foot tall man can see himself entirely? (Assume that both he and the mirror are vertical and that he places the mirror in the most favorable position.) Does it matter how far away he is from the mirror? Do your answers to these questions depend on the distance from his eyes to the top of his head?

13.8 Suppose the reflecting surfaces of every visible object were somehow altered so that they completely absorbed any light falling on them; how would the world then appear to you?



13.9 Objects are visible if their surfaces reflect light in many different directions, enabling our eyes to intercept cones of reflected light diverging from each part of the surface. The accompanying diagram shows such a cone of light (represented by 2 diverging rays) entering the eye from a book.
Draw clear straight-line diagrams to show how a pair of diverging rays can be used to help explain the following phenomena (here is a chance to use your knowledge of reflection and refraction):

a) The mirror image of an object appears to be just as far behind the mirror as the object is in front of the mirror.
b) A pond appears shallower than it actually is.
c) A coin placed in an empty coffee mug which is placed so that the coin cannot quite be seen becomes visible if the mug is filled with water.

13.10 Due to atmospheric refraction we see the sun in the evening for some minutes after it is really below the horizon, and also for some minutes before it is actually above the horizon in the morning.

a) Draw a simple diagram to illustrate how this phenomenon occurs.
b) The fact that this refraction by the atmosphere occurs is good evidence for the variation in density of the atmosphere; what does it indicate about the density variation?

13.11 Newton supposed that the reflection of light off shiny surfaces is due to "some feature of the body which is evenly diffused over its surface and by which it acts upon the ray without contact." The simplest model for such a feature would be a repulsive force which acts only in a direction perpendicular to the surface. In this question you are to show how this model predicts that the angles of incidence and reflection must be equal. Proceed as follows:

a) Draw a clear diagram showing the incident and reflected rays. Also show the angles of incidence and reflection (θ_i and θ_r). Sketch a coordinate system on your diagram that has an x-axis parallel to the surface and a y-axis perpendicular to the surface. Note that the angles of incidence and reflection are defined to be the angles between the incident and reflected rays and the y-axis.

b) Suppose that the incident light consists of particles of mass m and speed v, what is the kinetic energy of a single particle? Write mathematical expressions for the x and y components of the momentum of an incident light particle.

c) If the repulsive force due to the reflecting surface does no work on the particle and acts only perpendicular to the surface, which of the quantities that you have described in part (b) is (are) conserved?

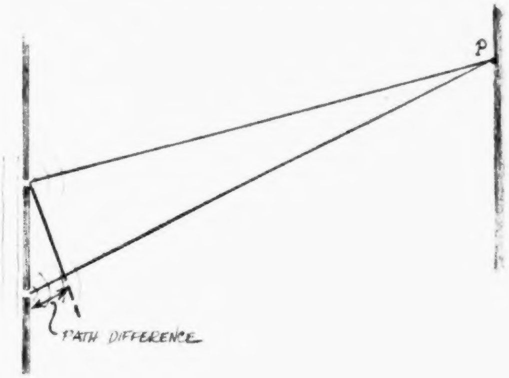
d) Show algebraically that the speed u of the reflected particle is the same as the speed v of the incident particle.

e) Write mathematical expressions for the components of the momentum of the reflected particle.

f) Show algebraically that θ_i and θ_r must be equal angles.

13.12 In a particle theory of light, refraction could be explained by assuming that the particle was accelerated by an attractive force as it passed from air or vacuum toward a medium such as glass. Assume that this accelerating force could act on the particle only in a direction perpendicular to the surface, and use vector diagrams to show that the speed of the particle in the glass would have to be greater than in air.

13.13



Plane parallel waves of single-wavelength light illuminate the two narrow slits, resulting in an interference pattern of alternate bright and dark fringes being formed on the screen. The bright fringes represent zones of constructive interference and hence appear at a point such as P on the diagram only if the diffracted waves from the two slits arrive at P in phase. The diffracted waves will only be in phase at point P if the path difference is a whole number of wavelengths (that is, only if the path difference equals $m\lambda$, where $m = 0, 1, 2, 3 \ldots$).

a) What values of the path difference would result in destructive interference at the screen?

b) The separation of the bright fringes depends on the wavelength of the light used. Would the separation be greater for red light or for blue light?

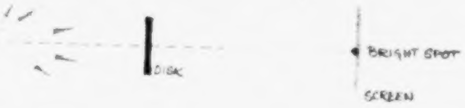
c) How would the pattern change if for a particular color the distance of the screen from the slits is increased? (Hint: make two diagrams.)

d) What changes occur in the pattern if the slits are moved closer together? (Hint: make two diagrams.)

e) What happens to the pattern if the slits themselves are made more narrow?

13.14 An interference pattern shows bright and dark fringes. What would you suppose becomes of the energy which is no longer present in the dark fringes?

13.15 Recalling diffraction and interference phenomena from Chapter 12, show that the wave theory of light can be used to explain the bright spot in the center of the shadow of a disk illuminated by a point source.



13.16 Green light has a wavelength of approximately 5×10^{-7} meters. What frequency corresponds to this wavelength? Compare this frequency to the frequency of the radio waves broadcast by a radio station you listen to. (Hint: Remember $v = f\lambda$.)

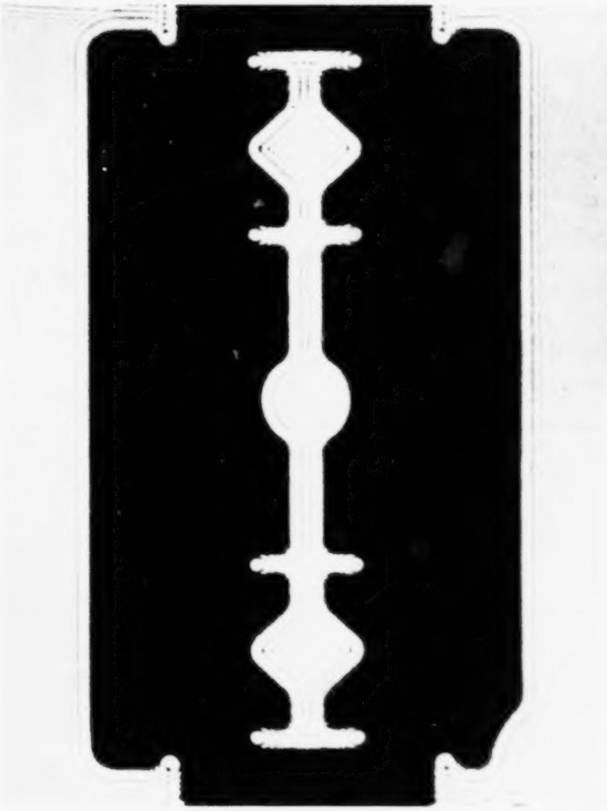
13.17 Poetry often reflects contemporary ideas in science; the following poem is an excellent example of this.

> Some range the colours as they parted fly,
> Clear-pointed to the philosophic eye;
> The flaming red, that pains the dwelling gaze,
> The stainless, lightsome yellow's gilding rays;
> The clouded orange, that betwixt them glows,
> And to kind mixture tawny lustre owers;
> All-chearing green, that gives the spring its dye:
> The bright transparent blue, that robes the sky;
> And indigo, which shaded light displays,
> And violet, which in the view decays.
> Parental hues, whence others all proceed;
> An ever-mingling, changeful, countless breed,
> Unravel'd, variegated, lines of light,
> When blended, dazzling in promiscuous white.
>
> Richard Savage, The Wanderer

a) Would you or would you not classify the poet Richard Savage as a "nature philosopher"? Why?
b) Compare this poem with the one in Sec. 13.5 by James Thomson; which poet do you think displays the better understanding of physics? Which poem do you prefer?

13.18 One way to achieve privacy in apartments facing each other across a narrow courtyard while still allowing residents to enjoy the view of the courtyard and the sky above the courtyard is to use polarizing sheets placed over the windows. Explain how the sheets must be oriented for maximum effectiveness.

13.19 To prevent car drivers from being blinded by the lights of approaching autos, polarizing sheets could be placed over the headlights and windshields of every car. Explain why these sheets would have to be oriented the same way on every vehicle and must have their polarizing axis at 45° to the vertical.



Diffraction fringes around a razor blade.

Chapter 14 Electric and Magnetic Fields

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An inside view of "Hilac:" heavy ion linear accelerator at Berkeley, California. In this device electric fields accelerate charged atoms to high energies.

14.1 Introduction. The subject "electricity and magnetism" makes up a large part of modern physics, and has important connections with almost all other areas of physics and chemistry. Because it would be impossible to study this subject comprehensively in the time available in an introductory course, we consider only a few major topics which will be needed as a foundation for later chapters. The major applications of the information in this chapter are: the development of electrical technology (Chapter 15), the study of the nature of light and electromagnetic waves (Chapter 16), and the study of properties of atomic and subatomic particles (Units 5 and 6).

In this chapter we will first treat electric charges and the forces between them—very briefly, since you are probably already somewhat familiar with this topic. Next, we will show how the idea of a "field" simplifies the description of electric and magnetic forces, especially in situations where several charges or magnetic poles are present.

An electric current is made up of moving charges. By combining the concept of field with the idea of "potential energy" (Unit 3), we will be able to establish quantitative relations between current, voltage and power. These relations will be needed for the practical applications to be discussed in Chapter 15.

At the end of this chapter we shall come to the relation between electricity and magnetism, a relation having important consequences both for technology and basic physical theory. We will begin by looking at a simple physical phenomenon: the interaction between moving charges and magnetic fields.

14.2 The curious properties of lodestone and amber: Gilbert's De Magnete. The substances amber and lodestone have aroused interest since ancient times. Amber is sap that long ago oozed from softwood trees and, over many centuries, hardened into a semitransparent solid ranging in color from yellow to brown. It is a handsome ornamental stone when polished, and it sometimes contains the remains of insects that were caught in the sticky sap. Ancient Greeks recognized a curious property of amber: if it is rubbed vigorously, it attracts nearby objects such as bits of straw or grain seeds.

Lodestone is a mineral with equally unusual properties. It attracts iron. When suspended or floated, a piece of lodestone turns to a particular orientation. The first known written description of the navigational use of lodestone as a compass dates from the late twelfth century. Its properties were known even earlier in China. Today lodestone would be called magnetized iron ore.

The histories of lodestone and amber are the early histories of magnetism and electricity. The modern developments in these subjects began in 1600 with the publication in London of William Gilbert's book De Magnete. Gilbert (1544-1603) was an influential physician, who served as Queen Elizabeth's chief physician. During the last twenty years of his life, he studied what was already known of lodestone and amber, made his own experiments to check the reports of other writers, and summarized his conclusion in De Magnete.

Gilbert's first task in his book was to review and criticize what had previously been written about the lodestone (see p. 37). Gilbert reports various theories proposed to explain the cause of magnetic attraction; one of the most popular theories was suggested by the Roman scientist Lucretius:

Lucretius is known as one of the early writers on atomic theory; see Prologue to Unit 5.

> Lucretius...deems the attraction to be due to this, that as there is from all things a flowing out ["efflux" or "effluvium"] of minutest bodies, so there is from iron an efflux of atoms into the space between the iron and the lodestone—a space emptied of air by the lodestone's atoms (seeds); and when these begin to return to the lodestone, the iron follows, the corpuscles being entangled with each other.

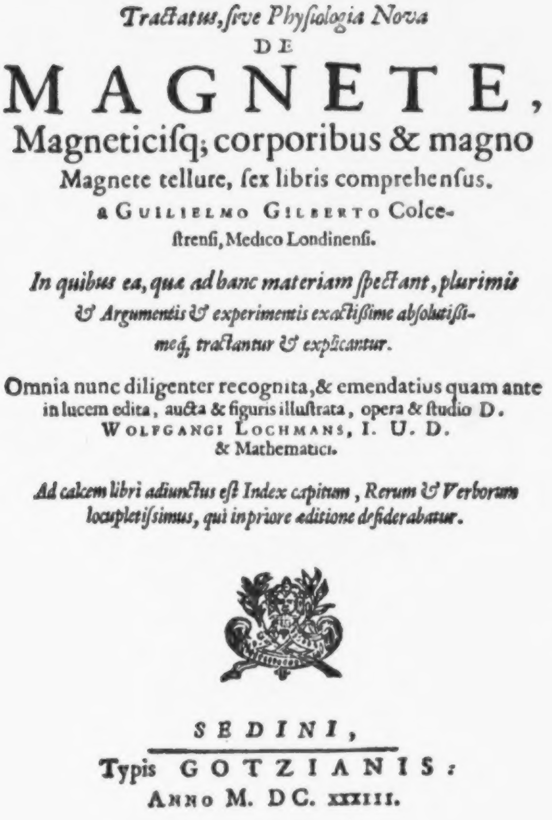
Gilbert himself did not accept the effluvium theory as an explanation for magnetic attraction, although he thought it might apply to electrical attraction.

When it was discovered that lodestones and magnetized bars of iron tend to turn so as to have a certain direction on the surface of the earth, many authors attempted to concoct explanations. But, says Gilbert,

> ...they wasted oil and labor, because, not being practical in the research of objects of nature, being acquainted only with books, being led astray by certain erroneous physical systems, and having made no magnetical experiments, they constructed certain explanations on a basis of mere opinions, and old-womanishly dreamt the things that were not. Marcilius Ficinus chews the cud of ancient opinions, and to give the reason of the magnetic direction seeks its cause in the constellation Ursa...Paracelsus declares that there are stars which, gifted with the lodestone's power, do attract to themselves iron....All these philosophers...reckoning among the causes of the direction of the magnet, a region of the sky, celestial poles, stars...mountains, cliffs, vacant space, atoms, attractional...regions beyond the heavens, and other like unproved paradoxes, are world-wide astray from the truth and are blindly wandering.

Gilbert's De Magnete is a classic in scientific literature. It included reports of intensive experiments and speculation about the magnetic properties of the earth. The richness of Gilbert's work is evident on the next page, where the title page, some excerpts and some sketches have been reproduced.

Gilbert himself pointed out the real cause of the motion of magnets: the earth itself is a lodestone. To demonstrate his theory Gilbert did an experiment, a rather ingenious one, to test his model: he prepared spherical lodestones and showed that a magnetized needle placed on the surface of such a lodestone will act in the same way as a compass needle does



Tractatus, ſive Phyſiologia Nova
DE
MAGNETE,
Magneticiſq; corporibus & magno
Magnete tellure, ſex libris comprehenſus.
a GUILIELMO GILBERTO Colceſtrenſi, Medico Londinenſi.

In quibus ea, quæ ad hanc materiam ſpectant, plurimis & Argumentis & experimentis exactiſsime abſolutiſsimeq; tractantur & explicantur.

Omnia nunc diligenter recognita, & emendatius quam ante in lucem edita, aucta & figuris illuſtrata, opera & ſtudio D. WOLFGANGI LOCHMANS, I. U. D. & Mathematici.

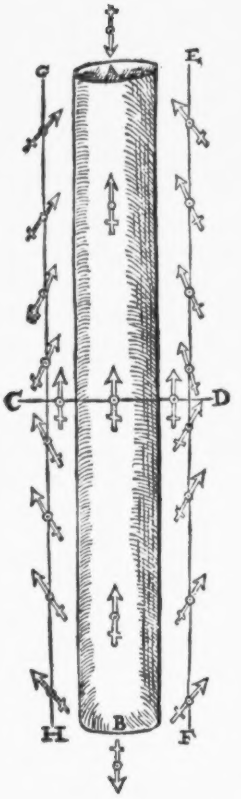
Ad calcem libri adiunctus eſt Index capitum, Rerum & Verborum locupletiſsimus, qui in priore editione deſiderabatur.

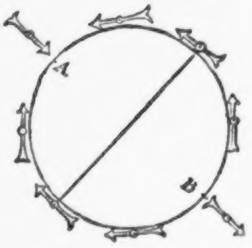
SEDINI,
Typis GOTZIANIS:
ANNO M. DC. XXXIII.

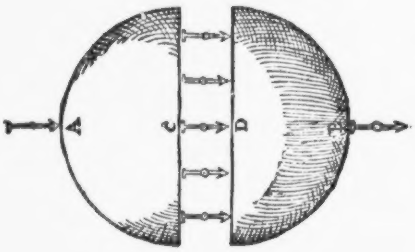
"...the lodestone was found, as seems probable, by iron-smelters or by miners in veins of iron ore. On being treated by the metallurgists, it quickly exhibited that strong powerful attraction of iron...And after it had come forth as it were out of darkness and out of deep dungeons and been honoured of men on account of its strong and marvellous attraction of iron, then many ancient philosophers and physicians discoursed of it...These record only that the lodestone attracts iron: its other properties were all hid. But lest the story of the lodestone should be uninteresting and too short, to this one sole property then known were appended certain figments and falsehoods...For example, they asserted that a lodestone rubbed with garlic does not attract iron; nor when it is in presence of a diamond.

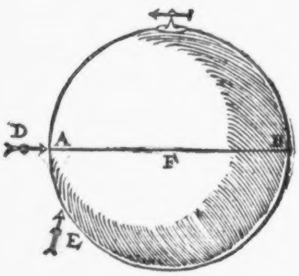
...we do not propose just now to overturn with arguments...the other many fables about the lodestone...Abohali rashly asserts, when held in the hand it cures pains of the feet and cramps;...as Pictorius sings, it gives one favor and acceptance with princes and makes one eloquent;...Arnoldus de Villanova fancies that the lodestone frees women from witchcraft and puts demons to flight; Marbodaeus, a Frenchman, says that it can make husbands agreeable to wives and may restore wives to their husbands. In such-like follies and fables do philosophers of the vulgar sort take delight..."

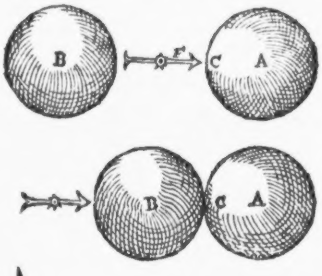
From Gilbert's *De Magnete*.

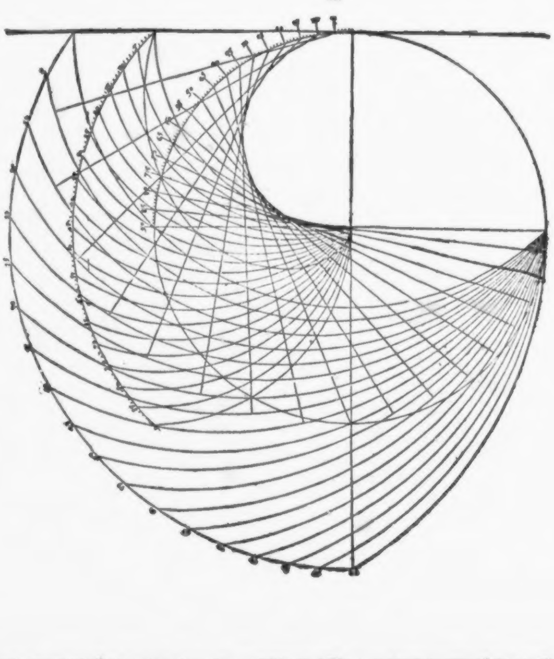












at different places on the earth's surface. If the directions of the needle are marked with chalk on the lodestone, they will form meridian circles (like the lines of equal longitude on a globe) which converge at two opposite ends or "poles." At the poles, the needle will be perpendicular to the surface of the lodestone. Halfway between, along the "equator," the needles will lie along the surface. These directions can also be shown by placing small bits of iron wire on the surface.

The idea of "field" was invented by Michael Faraday early in the nineteenth century, and developed further by Kelvin and Maxwell (see Secs. 14.4 and 16.2).

The explanation of the action of magnets is now generally given by means of the idea that magnets set up "fields" around themselves. The field can then act on distant objects. Gilbert's description of the force exerted by his spherical lodestone (which he called the 'terrella,' meaning 'little earth') comes close to the modern field concept:

> The terrella sends its force abroad in all directions, according to its energy and its quality. But whenever iron or other magnetic body of suitable size happens within its sphere of influence it is attracted; yet the nearer it is to the lodestone the greater the force with which it is borne toward it.

"electric" comes from the Greek word ἤλεκτρον, electron, meaning "amber." Note that this word was originally a noun but has now become an adjective.

Gilbert also included a discussion of electricity in his book. He introduced the word electric as the general term for "bodies that attract in the same way as amber." Gilbert showed that electric and magnetic forces are different. For example, a lodestone always attracts other magnetic bodies, whereas an electric exerts its attraction only when rubbed. On the other hand, an electric can attract small pieces of many different substances, whereas magnetic forces act only between a few types of substances. Objects are attracted to an electric along a line directly toward its center, but a magnet always has two regions (poles) toward which attraction draws other magnets.

Iron oxide crystals in the magnetic field of a bar magnet.

In addition to summarizing the known facts of electricity and magnets, Gilbert's work suggested new research problems to scientists in the centuries that followed. For example, Gilbert thought that while the poles of two lodestones might repel each other, electrics could never exert repulsive forces. But in 1646, Sir Thomas Browne published the first account of electric repulsion, and in the eighteenth century several other cases of repulsion as well as attraction were discovered. To systematize these observations a new concept, electric charge, was introduced. In the next section we will see how this concept can be used to describe the forces between electrified bodies.

Q1 How did Gilbert demonstrate that the earth behaves like a spherical lodestone?

Q2 How does the attraction of objects by amber differ from the attraction by lodestone?

14.3 Electric charges and electric forces. As Gilbert strongly argues, the facts of electrostatics (forces between electric charges at rest) are better learned in the laboratory than by just reading about them. This section, therefore, is only a brief summary.

We begin with the idea of electric charge. Charge is best defined not by saying what it is, but what it does. Two kinds of electric charges can be identified. A glass rod that has been rubbed by silk becomes charged. This charge is given the arbitrary name positive charge. The other kind of charge appears on a rubber rod stroked with wool or fur and is termed negative.

When we talk about the electric charge on an object we usually mean the slight excess (or net) charge of either kind existing on this object. Actually, any piece of matter large enough to be visible contains a large amount of electric charge, both positive and negative. If the amount of positive charge is equal to the amount of negative charge, this piece of matter will appear to have no charge at all, so we can say that the effects of the positive and negative charges simply cancel each other when they are added together. (This is one advantage of calling the two kinds of charge positive and negative, rather than, for example, x and y.)

Rarely is this imbalance more than 1 part in 1 million-million.

Two experimental facts that are easily demonstrated are the following:

1. Like charges repel each other. A body that has a net positive charge repels any other body that has a net positive charge. That is, two glass rods that have both been rubbed will tend to repel each other. A body that has a net negative charge repels any other body that has a net negative charge.

2. Unlike charges attract each other. A body that has a net positive charge attracts any body that has a net negative charge, and vice versa.

Benjamin Franklin (1706-1790), American statesman, printer, scientist and writer. He was greatly interested in the phenomena of static electricity; his famous kite experiment and invention of the lightning rod gained him wide recognition; he is shown here observing the electrical behavior of a bell connected to a lightning rod. His other inventions include the Franklin stove, bifocals and the harmonica. While in Philadelphia, Franklin organized a debating club which developed into the American Philosophical Society, and he helped establish an academy which later became the University of Pennsylvania.

The electrical force law. What is the "law of force" between electric charges? In other words, how does the force depend on the amount of charge, and on the distance between the charged objects?

The first evidence of the nature of the force law between electrical charges was obtained in an indirect way. About 1775, Benjamin Franklin performed the following experiment: He charged a silver can and put the can on an insulating stand. When he hung a cork near the outside of the can, the cork was strongly attracted. But when he lowered the cork, suspended by a silk thread, into the can, he found that no electric force was exerted on the cork no matter what its position was inside the can.

Joseph Priestley (1733-1804), a Unitarian minister, was persecuted in England for his radical ideas. One of his books was burned, and a mob looted his house because of his sympathy with the French Revolution. He moved to America, the home of Benjamin Franklin, who had stimulated Priestley's interest in science. He developed carbonated drinks (soda-pop) and experimented in electricity, in addition to his well-known work on oxygen.

Franklin did not understand why the walls of the can did not attract the cork when it was inside the can, even though there was a force when the cork was outside. He asked his friend Joseph Priestley to repeat the experiment.

Priestley verified Franklin's results, and went on to make a brilliant theoretical deduction from them. He remembered from Newton's Principia that Newton had proved that gravitational forces behave in a similar way. Inside a hollow sphere, the net gravitational force on an object, computed by adding up all the forces exerted by the parts of the sphere, is exactly zero. This is a result which can be deduced mathematically from the law that the gravitational force between any two individual pieces of matter is inversely proportional to the square of the distance between them. Priestley therefore proposed that electrical forces might also vary inversely as the square of the distance. (See page 42.)

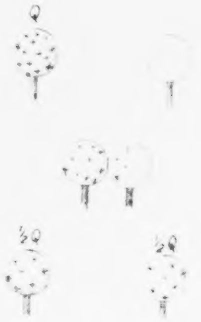
Priestley's proposal was based on bold reasoning by analogy. Such reasoning could not by itself prove that electrical forces are inversely proportional to the square of the distance between charges. But it strongly encouraged other physicists to test the hypothesis by experiment.

The French physicist Charles Coulomb provided direct experimental confirmation of the inverse-square law for electric charges suggested by Priestley. Coulomb used a torsion balance that he invented and carefully calibrated to measure the force between two small charged spheres. The balance is shown on the opposite page. A balanced insulating rod is shown suspended by a thin silver wire which twists when a force is exerted on the end of the rod to make it rotate about the vertical axis.

By measuring the twisting force for different separations R of the spheres, Coulomb showed that the force varied in proportion to $1/R^2$. Thus he directly confirmed the suggestion that the force of electrical repulsion for like charges varies inversely as the square of the distance between charges. With a slightly modified procedure, he confirmed a similar law of attraction for unlike charges.

The symbol q is used for amount of charge; see below for units.

Coulomb also demonstrated that the magnitude of the electric force at a given distance is proportional to the product of the charges, q_Aq_B, on the two objects. This was a remarkable accomplishment, since there was not yet any accepted method for measuring quantitatively the amount of charge on an object. However, Coulomb could show that if a charged metal sphere touches an uncharged sphere of the same size, the total charge will be shared between the two spheres equally. Thus, starting with a given amount of charge on one sphere and several other identical but uncharged spheres, Coulomb could produce charges of one-half, one-quarter, one-eighth, etc., the original amount. By thus varying the charges q_A and q_B independently, he could show, for example, that when each is reduced by one-half, the force between A and B is reduced to one-quarter its previous value.

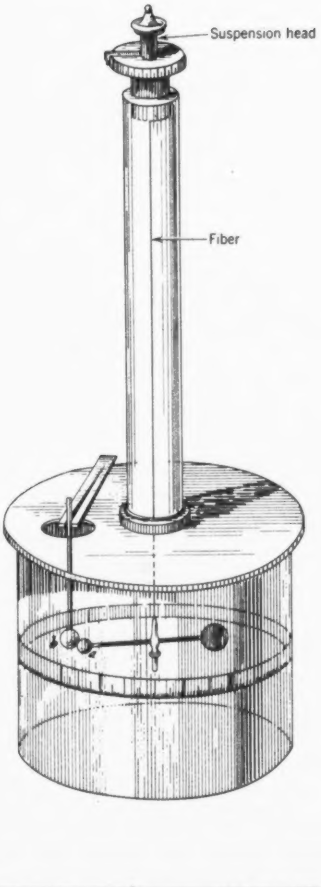


Coulomb summarized his results in a single equation which describes the force that two small charged spheres A and B exert on each other:

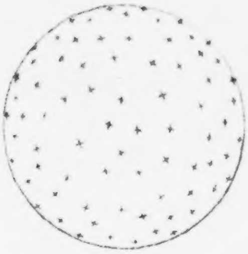
$$F_{el} = k \frac{q_A q_B}{R^2} \qquad (14.1)$$

where k is a constant whose value depends on the units of charge and length that are being used. This form of the law of force between two electric charges is now called Coulomb's law.

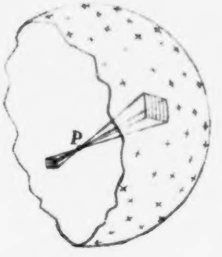
Charles Augustin Coulomb (1738-1806) was born into a family of high social position and grew up in an age of political unrest. He studied science and mathematics and began his career as a military engineer. He later settled in Paris, and a work, The Theory of Simple Machines, gained him membership in the French Academy of Sciences. While studying machines Coulomb invented his torsion balance, with which he carried out intensive investigations on electrical forces.



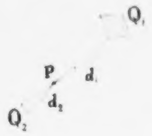
The documentary film "People and Particles" shows an experiment to see if Eq. 14.1 applies to charges at distances as small as 10^{-15} cm. (It does.)



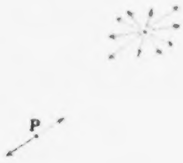
Consider any point P inside a charged conducting sphere. For any small patch of charge on the sphere there is a corresponding patch on the other side of P.



The electric field due to each patch is proportional to the area of the patch and inversely proportional to the square of the distance from P. But the areas of the patches are directly proportional to the squares of the distances from P.



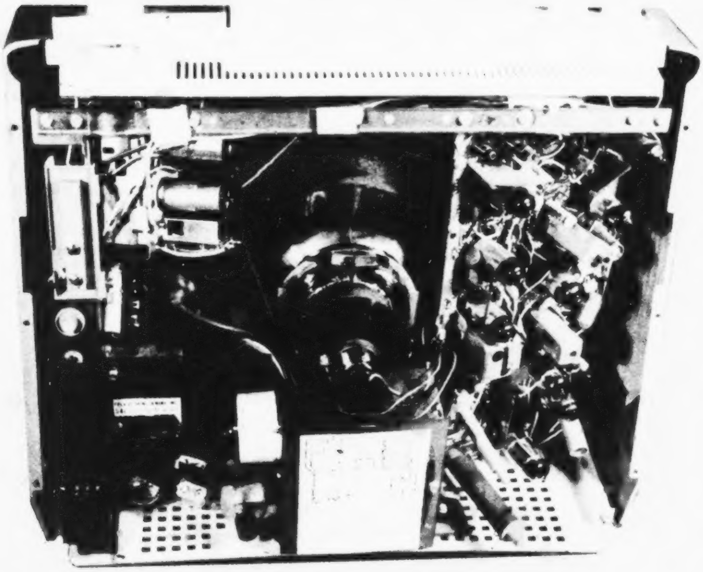
So the distance and area factors balance—the fields due to the two patches at P are exactly equal and opposite.



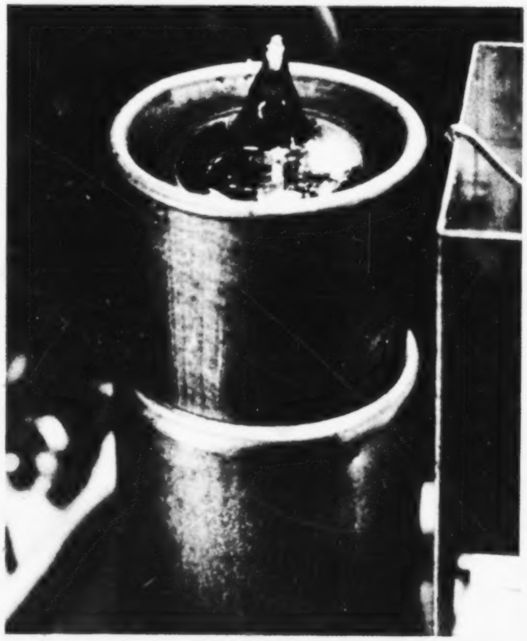
Since this is true for all pairs of charge patches, the net electric field at P is zero.

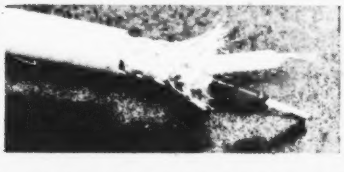
Electric Shielding

In general, charges on a closed conducting surface arrange themselves so that the electric field strength inside is zero (on the condition, of course, that there is no charge inside). Furthermore, the region inside any closed conductor is "shielded" from any external electric field. This is a very important practical principle. Whenever stray electric fields might disturb the operation of some electric equipment, the equipment can be enclosed by a shell of conducting material. Some uses of electric shielding are suggested in the accompanying photographs.



Closeup of a tube in the tuning section of the TV set on the left. Surrounding the tube is a collapsible metal shield. Partly shielded tubes can be seen elsewhere in that photo.



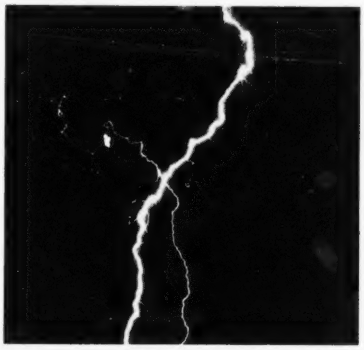


A section of shielded cable such as is seen in the TV photo above, showing how the two wires are surrounded by a conducting cylinder woven of fine wires.

Meter-Kilogram-Second-Ampere

The unit of charge. We could use Eq. (14.1) to define a unit of charge. For example, we could arbitrarily let the magnitude of k be exactly 1 and define a unit charge so that two unit charges separated by a unit distance exert a unit force on each other. There is a set of units based on this choice. However, in the system of electrical units we shall find more convenient to use, the "MKSA" system, the unit of charge is derived from the unit of current, the "ampere." The unit of charge is called the "coulomb," and is defined as the amount of charge that flows past a point in a wire in one second when the current is equal to one ampere.

The ampere, or "amp," is a familiar unit because it is frequently used to measure the current drawn by electrical appliances. The amount of current drawn by a 100-watt light bulb in a 110-volt circuit is approximately one ampere.

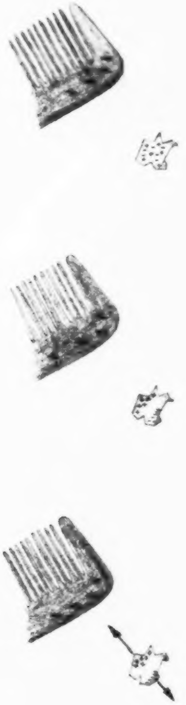


A stroke of lightning averages about 40,000 amperes and transfers 1 coulomb of charge from the cloud to the ground, or vice versa.

Since one coulomb is approximately the amount of charge that goes through a 100-watt bulb in one second, it might seem that the coulomb is a fairly small amount of charge. However, one coulomb of excess charge all collected in one place is unmanageably large. By experiment, the constant k in Coulomb's law (Eq. 14.1) is found to equal about nine billion newton-meters squared per coulomb squared (9×10^9 $Nm^2/coul^2$). This means that two objects, each with a net charge of one coulomb, separated by a distance of one meter, would exert forces on each other of nine billion newtons. This force is roughly the same as a weight of one million tons. We never observe such large forces, because we can't actually collect that much excess charge in one place, or exert enough force to bring two such charges so close together. The mutual repulsion of like charges is so strong that it is difficult to keep a charge of more than a thousandth of a coulomb on an object of ordinary size. If you rub a pocket comb on your sleeve, the net charge on the comb will be far less than one millionth of a coulomb. Lightning discharges usually take place when a cloud has accumulated a net charge of a few hundred coulombs distributed over its very large volume.

The reason that an ordinary light bulb can have one coulomb per second going through its filament is that the moving charges, which in this case are negative, are passing through a static arrangement of positive charges.

Electrostatic induction. You have probably observed that an electrically charged object can often attract small pieces of paper even though the paper seems to have no net charge itself. (It exerts no force on other pieces of paper.) At first sight it might appear that this attraction is not covered by Coulomb's law, since the force ought to be zero if



either q_A or q_B is zero in Eq. (14.1). However, we can explain the attraction if we recall that uncharged objects contain equal amounts of positive and negative electric charges. When an electrified body is brought near a neutral object, electrical forces may rearrange the positions of the charges in the neutral object (see diagram). For example, if a negatively charged rod is held near a piece of paper, some of the positive charges in the paper will shift toward the side of the paper nearest the rod, and a corresponding amount of negative charge will shift toward the other side. The positive charges are then slightly closer to the rod than the negative charges are, so the attraction is greater than the repulsion. (Remember that the force gets weaker with the square of the distance, according to Coulomb's law; it would only be one fourth as great if the distance were twice as large.) Hence there will be a net attraction of the charged body for the neutral object.

The rearrangement of electric charges inside or on the surface of a neutral body due to the influence of a nearby object is called electrostatic induction. In Chapter 16 we will see how the theory of electrostatic induction played an important role in the development of the theory of light.

Q3 What experimental fact led Priestley to propose that electrical forces and gravitational forces change with distance in a similar way?

Q4 What two facts about the force between electric charges did Coulomb demonstrate?

Q5 If the distance between two charged objects is doubled, how is the electrical force between them affected?

Q6 Are the coulomb and ampere both units of charge?

Q7 If an object is found to be attracted by both positively charged bodies and negatively charged bodies, does this mean that there are really three kinds of charge?

14.4 Forces and fields. Gilbert described the action of the lodestone by saying it had a "sphere of influence" surrounding it. Any other magnetic body coming inside this sphere will be attracted, and the strength of the attractive force will be greater at places closer to the lodestone. In modern language, we would say that the lodestone is surrounded by a magnetic field.

Because the word "field" is used in many ways, we will begin by discussing some familiar fields and then proceed gradually to develop the ideas of physical fields.

One part of the concept of field is illustrated by playing fields. The football field, for example, is a place where teams compete according to rules which confine the significant action to the area of the field. The field is a region of interaction.

In international politics, we speak of spheres or fields of influences. A field of political influence is also a region of interaction but, unlike a playing field, it has no sharp boundary line. A country usually has greater influence on nearby countries and less influence on countries farther away. So in the political sense, "field" implies also an amount of influence, which can be stronger in some places and weaker in others. Furthermore, the field has a source—the country exerting the influence. The strength of the influence depends on how strong the first country is, as well as on the location in the field.

We are now fairly close to the concept of field as used in physics; the political field of influence implies a region of interaction in which there are different amounts of influence produced by some source. One step remains. The influence of a political field is exerted mainly on governments, which are geographically very small parts of the field region. To define a field in the physical sense, it must be possible to assign a value of field strength to every point in the field. This part of the field idea will become clear as we discuss now some fields which are more directly related to the study of physics. First we will talk about them in everyday language; then we will introduce the terminology of physics.

The Situation	Description of your experience
a) You are walking along the sidewalk toward a street lamp at night.	"The amount of light is increasing."
b) You stand on the sidewalk as an automobile comes down the street with its horn blasting.	"The sound gets louder and then softer."
c) On a hot summer day, you walk barefoot out of the sunshine and into the shade on the sidewalk.	"The sidewalk is cooler here than in the sunshine."

We can describe these experiences in terms of fields:

a) The street lamp is surrounded by a field of illumination. The closer you get to the lamp, the stronger the illumination where you are. For every place near the street lamp, we could assign a number that represents the strength of illumination at that place.

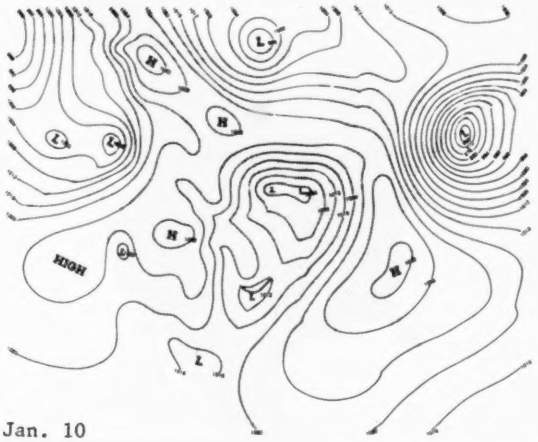
b) The horn is surrounded by a sound field. In this case you are standing still in your frame of reference (the sidewalk) and a pattern of field values goes past you with the

Pressure and Velocity Fields

These maps, adapted from those of the U.S. Weather Bureau, depict two fields, air pressure at the earth's surface and high-altitude wind velocity, for three successive days.

Air pressure at earth's surface.

High altitude wind velocity.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HIGH
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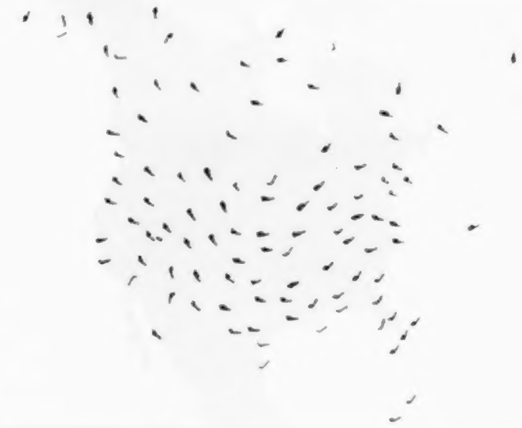
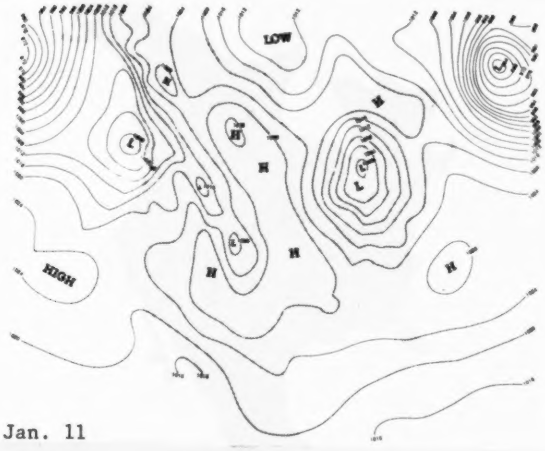
H
L
L

Jan. 10




LOW
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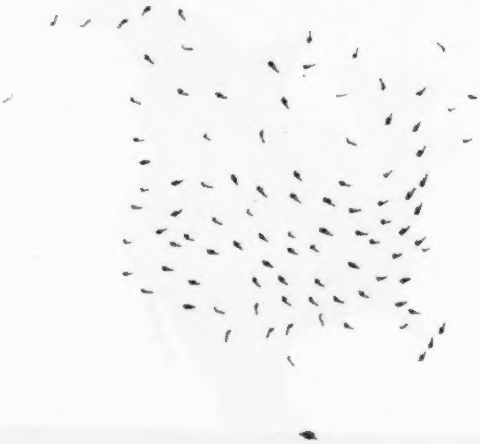
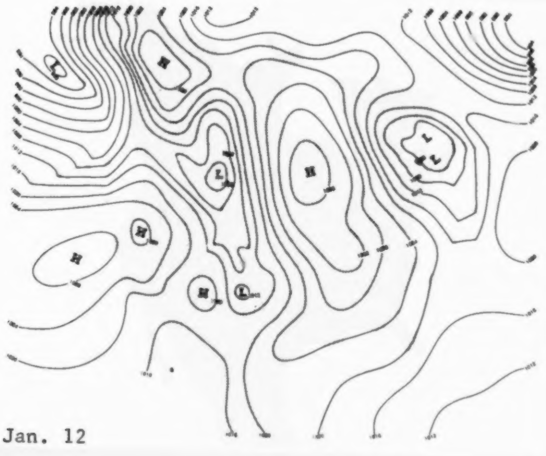
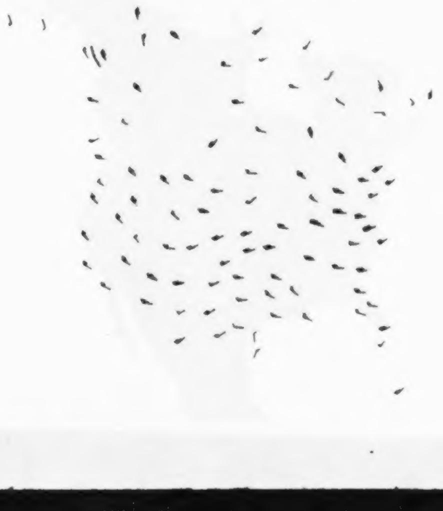
Jan. 11





Jan. 12



same speed as the car. We can think of the sound field as being steady but moving with the horn. At any instant we could assign a number to each point in the field to represent the intensity of sound. At first the sound is faintly heard as the weakest part of the field reaches you. Then the more intense parts of the field go by, and the sound seems louder. Finally, the loudness diminishes as the sound field and its source (the horn) move away.

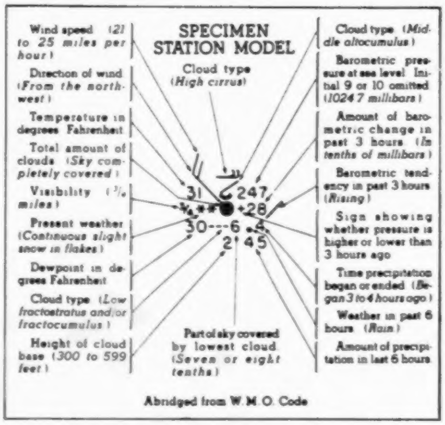
c) Here you are walking in a temperature field which is intense where the sidewalk is in the sunshine and weaker where it is in the shade. Again, we could assign a number to each point in the field to represent the temperature.

Notice that the first two of these fields are produced by a single source. In (a) the source is a stationary street lamp, in (b) it is a moving horn. In both cases the field strength gradually decreases as your distance from the source increases. But in the third case the field is produced by a complicated combination of influences: the sun, the clouds in the sky, nearby buildings, local geography and other factors. Yet the description of the field itself may be just as simple as for a field produced by a single source: one number is assigned to each point in the field.

So far, all examples were simple scalar fields—no direction was involved in the value of the field at each point. On the opposite page are maps of two fields for the layer of air over the surface of North America for three consecutive days. There is a very important difference between the field mapped at the left and that mapped at the right; the air pressure field is a scalar field, while the wind velocity field is a vector field. For each point in the pressure field, there is a single number, a scalar quantity which gives the value of the field at that point. But for each point in the wind velocity field the value of the field is given by both a number and a direction, that is, by a vector.

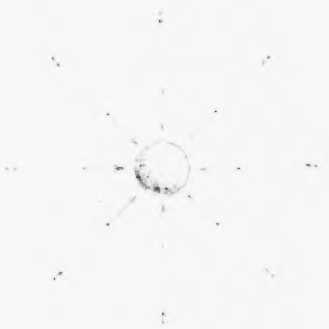
These field maps are particularly useful, because they can be used more or less successfully to predict what the subsequent conditions of the field might be. Also, by superimposing the maps on each other, we could get some idea of how the fields are related to each other.

The term "field" is actually used by physicists in three different senses: to mean the value of the field at a point in space, the collection of all values, and the region of space in which the field has values. In reading the rest of this chapter, try to decide which meaning is appropriate each time the term is used.


SPECIMEN STATION MODEL
Cloud type (High cirrus)
Wind speed (21 to 25 miles per hour)
Direction of wind (From the northwest)
Temperature in degrees Fahrenheit
Total amount of clouds (Sky completely covered)
Visibility (¾ miles)
Present weather (Continuous slight snow in flakes)
Dewpoint in degrees Fahrenheit
Cloud type (Low fractostratus and/or fractocumulus)
Height of cloud base (300 to 599 feet)
Part of sky covered by lowest cloud (Seven or eight tenths)
Cloud type (Middle altocumulus)
Barometric pressure at sea level. Initial 9 or 10 omitted (1024.7 millibars)
Amount of barometric change in past 3 hours (In tenths of millibars)
Barometric tendency in past 3 hours (Rising)
Sign showing whether pressure is higher or lower than 3 hours ago
Time precipitation began or ended (Began 3 to 4 hours ago)
Weather in past 6 hours (Rain)
Amount of precipitation in last 6 hours
31
247
¾
+28
30
6
4
2
45
Abridged from W.M.O. Code

Key for a U.S. Weather Bureau Map. How many fields are represented for each station?

14.4



The gravitational field. Before returning to electricity and magnetism, and just to illustrate the idea of a field, we take as an example the gravitational field of the earth. Recall that the force exerted by the earth on some object outside the surface of the earth, for example upon the moon, acts in a direction toward the center of the earth. The gravitational field is a vector field and could be represented by arrows pointing toward the center of the earth.

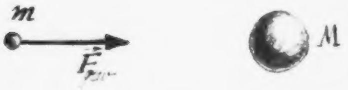
The strength of the gravitational field depends on the distance from the center of the earth, since, according to Newton's theory, the magnitude of the gravitational force is inversely proportional to the square of the distance R:

$$F_{grav} = G\frac{Mm}{R^2} \qquad (14.2)$$

where M is the mass of the earth, m is the mass of the test body, and R is the distance between the centers of earth and other body (G is the gravitational constant).

Is the value of the gravitational field at each point just the same as F_{grav} exerted on a body at that point? No, because F_{grav} depends on the mass of the test body, and we want our definition of field to depend only on the properties of the source, not on the properties of the test body on which the force acts. The force itself must of course depend on the mass of the test body, but it is useful to think of the field as existing in space and having a certain direction and magnitude at every point, whether or not there is any test body present for it to act on.

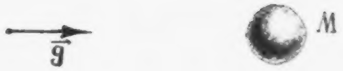
From now on, "field" is defined to be independent of the test body on which a force may act.



A definition of gravitation field that satisfies the above requirement follows easily if we rearrange Eq. (14.2):

$$F_{grav} = m\frac{GM}{R^2}$$

We then define the gravitational field, $\vec{g}$, to have a magnitude $\frac{GM}{R^2}$ and the same direction as that of $\vec{F}_{grav}$. Thus $\vec{g}$ is determined by the strength of the source (the mass M) and the distance (R) from the source but does not depend on the mass of the object which the force acts upon. The force is then simply the product of the mass of the test body and the field,



$$\vec{F}_{grav} = m\vec{g} \qquad (14.3)$$

and

$$\vec{g} = \frac{\vec{F}_{grav}}{m} \qquad (14.4)$$

SG 14.5

In other words, the gravitational field at a point in space is defined as the quotient of the gravitational force which would act on a body of mass m at that point, and the mass m. However, the gravitational field at a point in space is determined by more than one source. The moon is acted on by the sun as well as by the earth, and to a smaller extent by the other planets. Thus, to generalize Eq. (14.4), we can take $\vec{F}_{grav}$ to be not just the force of gravity due to one source, but the net gravitational force due to all sources acting on that region.

Electric fields. In general, the strength of any force field can be defined in the same way as for gravitational fields if there is a force law similar to Newton's in which the force is proportional to a product of quantities characteristic of the two interacting bodies. Thus for electric forces, according to Coulomb's law (Eq. 14.1), the force depends on the product of the charges of the two bodies, rather than the product of the masses. For a charge q in the electric field due to charge Q, Coulomb's law describing the force on q can be written as:

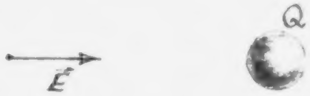
$$F_{el} = k\frac{Qq}{R^2} \quad \text{or} \quad F_{el} = q\frac{kQ}{R^2} .$$

As in the case of the gravitational field, the expression for force has been broken up into two parts. One part, $\frac{kQ}{R^2}$, which depends only on the "strength" Q of the source and distance R from it, is the electric field due to Q. The second part, q, is a property of the body being acted on. Thus we define the electric field, $\vec{E}$, due to charge Q to have magnitude $\frac{kQ}{R^2}$, and the same direction of $\vec{F}_{el}$. The electric force is then the product of the test charge and the field,

$$\vec{F}_{el} = q\vec{E} \tag{14.5}$$

and

$$\vec{E} = \frac{\vec{F}_{el}}{q} \tag{14.6}$$

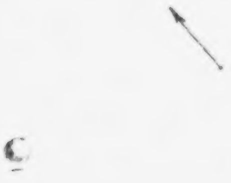


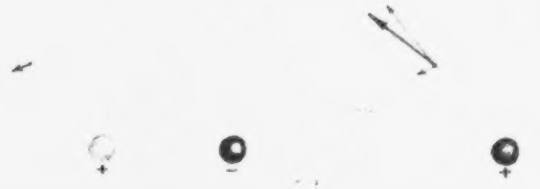
Therefore the electric field at a point in space is defined as the quotient of the electric force acting on a test charge placed at that point and the magnitude of the test charge. Of course, if the electric field at a point is due to more than one source, we define the electric field in terms of the net electric force on test charge q.

SG 14.6
SG 14.7
SG 14.8

So far we have passed over a complication that we did not encounter in dealing with gravitation. There are two kinds of electric charge, positive (+) and negative (-), and the forces they experience in an electric field are opposite in direction. Long ago the arbitrary choice was made of defining the field value as the force exerted on a positive charge, divided by the magnitude of that charge. This choice makes it easy to remember the direction of the electric force vector, if we adopt the convention that a minus sign in front of a vector means that it has the opposite direction. If we are given the direction and magnitude of the field vector $\vec{E}$ at a

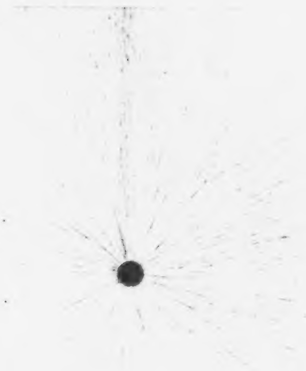
Visualizing Electric Fields



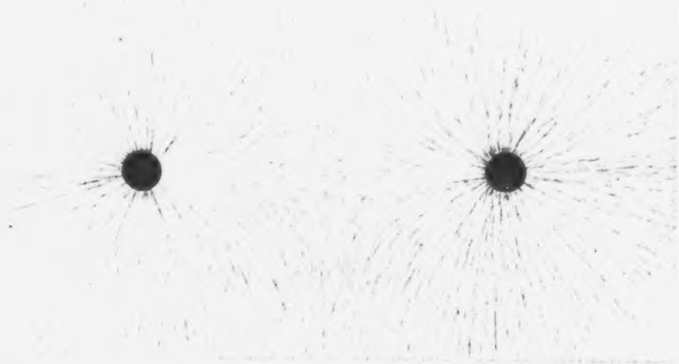


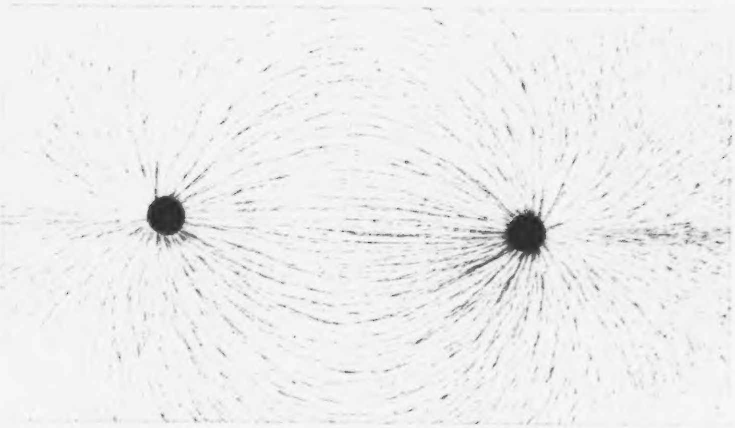
Rarely will we be interested in the field of a single charged sphere. If we want to be able to calculate the field values for a complicated array of charges, without actually taking some small test charge and moving it around in the field to measure the force, we need a rule for adding the field values of separate sources. A wide variety of experiments indicates that, at any point in an electric field, the field value produced by a combination of sources is just the vector sum of the field values produced by each source alone. Although we can be sure of this simple vector addition only to the limits of experimental accuracy, physicists assume that the principle is absolutely true.

A simple example of adding fields is finding the electric field produced by a pair of spheres with equal charges of opposite sign. The first frame in the margin indicates the field strength at a point P which would result from the presence of the (+) charge alone. The second frame shows the field strength at the same point which would result from the presence of the (-) charge alone. (The point P happens to be twice as far from the negative charge as from the positive charge, so the field strength is only ¼ as great.) When both (+) and (-) charges are present, the electric field strength at the point is the vector sum of the individual field strengths, as indicated in the third frame.



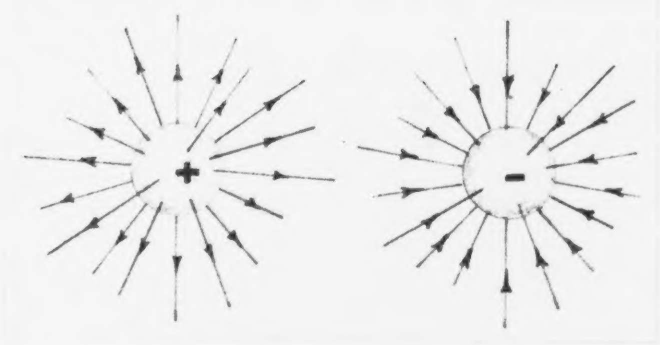
Similarly charged spheres

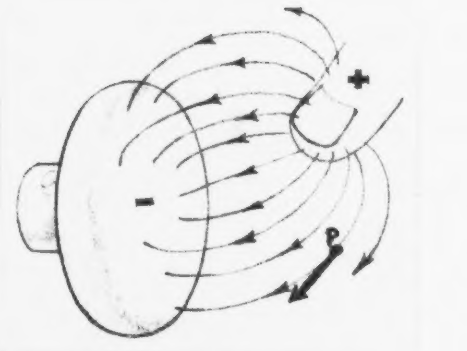




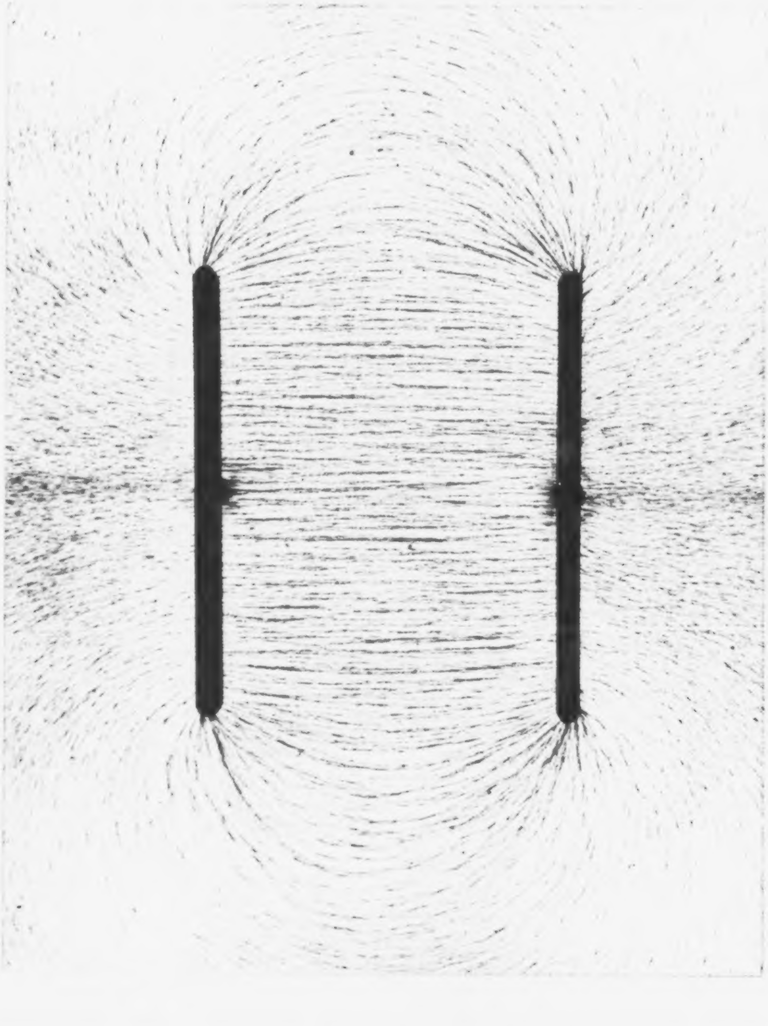
These five photographs of objects in an electric field show fine fibre clippings suspended in oil. An electric field induces opposite charges on the two ends of every clipping. The clipping then lines up in the field.

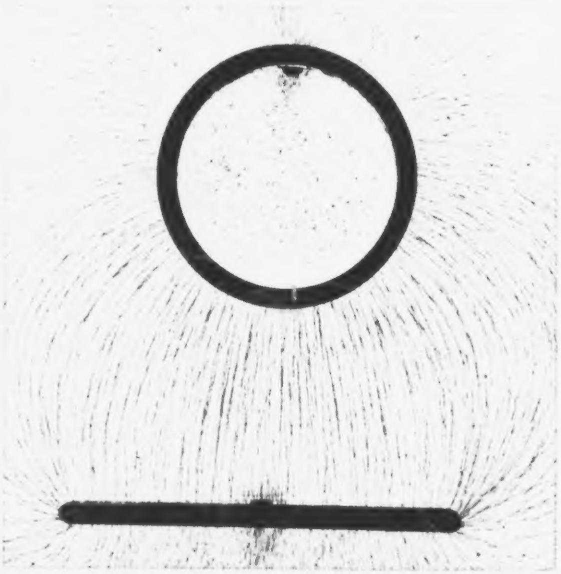
Oppositely charged spheres





The map of an electric field is not easy to draw. A vector value can be assigned to the electric field strength at every point in space, but obviously we cannot illustrate that—our map would be totally black with arrows. The convention which has been used for many years in physics is to draw a small number of lines which indicate the direction of the field. For example, the field around a charged sphere could be represented by a drawing like that in the margin. Notice that the lines, which have been drawn symmetrically around the sphere, are more closely spaced where the field is stronger. In fact, the lines can be drawn in three dimensions so that the density of lines represents the strength of the field. These lines, drawn to represent both the direction and strength of the field, are called "lines of force." Around a single charged sphere the lines of force are straight and directed radially away from the center. When charge is distributed in a more complicated way, the lines of force may be curved. The direction of the field at a point is the tangent to the curved line of force at that point. Above, for example, we have drawn lines of force to represent the direction of the electric field between a charged fingertip and the oppositely charged surface of a doorknob. The electric field vector $\vec{E}$ at point P would be directed along the tangent to the curved line of force at P, and represented by the arrow at P. Note the difference: each line of force only shows direction, and terminates at a charged object or goes off to infinity. But the electric field vector $\vec{E}$ at each point P is represented by an arrow of length drawn to scale to indicate magnitude E.





Oppositely charged cylinder and plate. (Notice the absence of field inside the cylinder.)

Oppositely charged plates. (Notice the uniformity of the field between them.)

SG 14.9

point, then by definition the force vector $\vec{F}$ acting on a charge q is $\vec{F} = q\vec{E}$. A positive charge, say +0.00001 coulombs, placed at this point will experience a force $\vec{F}$ in the same direction as $\vec{E}$. A negative charge, say -0.00001 coulombs, will experience a force $-\vec{F}$ of the same magnitude as $\vec{F}$ but in the opposite direction. Changing the sign of q automatically changes the direction of $\vec{F}$.

Q8 What is the difference between a scalar field and a vector field?

Q9 What is the direction of
a) the gravitational field, and
b) the electric field, at a certain point in space?

Q10 Why would the field strengths $\vec{g}$ and $\vec{E}$ be unchanged in Equations (14.4) and (14.6) if m and q were doubled?

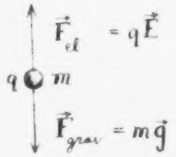
14.5 The smallest charge. How strong are electric forces? In Sec. 14.3 we mentioned the fact that an electrified comb can pick up a small piece of paper, so that in this case the electric force on the paper must exceed the gravitational force exerted on it by the earth. But before we can discuss such questions quantitatively, we will introduce a more natural or fundamental unit of charge which can always be associated with an object that has a definite mass. In modern physics it is most convenient to use the charge of an electron, one of the basic components of the atom. (Other properties of atoms and electrons will be discussed in Unit 5.)

A remarkable illustration of the strength of electric forces is the fact that, using an electric field that can be produced easily in the laboratory, we can balance the gravitational force on a tiny object, only big enough to be seen in a microscope but still containing several billion atoms, with the electrical force on a single electron. This fact is the basis of a method of measuring the electron charge in an experiment first done by the American physicist Robert A. Millikan in 1909. Although a further description of Millikan's experiment will be postponed until Sec. 18.3, its basic principle will be discussed here because it provides such a vivid connection between the ideas of force, field and charge.

Suppose a small body of mass m—an oil drop or small plastic sphere—carries a net negative electric charge of magnitude q. If we place the negatively charged body in an electric field $\vec{E}$ directed downwards, there will be exerted on the body a force of magnitude qE in the upward direction. Of course there will also be a downward gravitational force mg on the object. The body will accelerate upward or downward,

Millikan chose fine droplets of oil from an atomizer to get very small masses. Also, the oil was convenient because of the low rate of evaporation of the droplet.

depending on whether the electric force or the gravitational force is greater. By adjusting the magnitude of $\vec{E}$, that is by changing the source that sets up a known electric field $\vec{E}$, we can balance the two forces.



What happens when the two forces are balanced? Remember that if no forces act on a body it can still be moving with constant velocity. However, in this case air resistance will soon destroy any original motion which the oil drop may have (when the oil drop is stationary, no frictional forces act on it); the drop will then be in equilibrium and will be seen to be suspended in mid-air. When this happens, we record the magnitude of the electric field strength E.

When mg and qE are balanced, frictional forces remain until the body stops moving.

If the electric force balances the gravitational force, the following equation must hold:

$$qE = mg. \tag{14.7}$$

If we know the quantities E, m and g, we can calculate q from this equation:

$$q = \frac{mg}{E}\ . \tag{14.8}$$

Let us assume that all possible charges in nature must be made up of multiples of some smallest charge, which we call e, the magnitude of the charge on the electron. (As we shall see, the results of the experiment confirmed the validity of this assumption.) Then we can write q = ne where n is a whole number.

The magnitude of the charge on the electron is e; its sign is negative.

To determine e from this equation, we would need to know n, the number of electron charges which make up the total charge q. We do not know n, but it is possible to calculate e, nevertheless, by repeating the experiment many times with a variety of small charges. If there is a smallest "electron charge," e, then all the values of q which we obtain from this experiment should be multiples of that charge. For example, if all apples had the same mass, we could infer the mass of one apple by weighing several small bags of apples and looking for the largest common factor of each result. This is in effect what Millikan did, although he used many experimental refinements and a variety of measurement techniques. He arrived at the value for the electron charge of $e = 1.6024 \times 10^{-19}$ coulomb. (For most purposes we can use the value of 1.6×10^{-19} coulomb.) This value agrees with the results of many other experiments done subsequently. No experiment has yet revealed a smaller unit of charge.

SG 14.11
SG 14.12
SG 14.13

Q11 How can the small oil droplets or plastic spheres used in the Millikan experiment experience an electric force upward if the electric field is directed downward?

Q12 What do the results of the Millikan experiment indicate about the nature of electric charge?

14.6 Early research with electric charges. For many centuries the only way known to charge objects electrically was to rub them by hand. In 1663, Otto von Guericke made and described a machine that would aid in producing large amounts of charge by rubbing.

> ...take a sphere of glass which is called a phial, as large as a child's head; fill it with sulphur that has been pounded in a mortar and melt it sufficiently over a fire. When it is cooled again break the sphere and take out the globe and keep it in a dry place. If you think it best, bore a hole through it so that it can be turned around an iron rod or axle....

When he rested his hand on the surface of the sulphur globe while rotating it rapidly, the globe acquired enough charge to attract small objects.

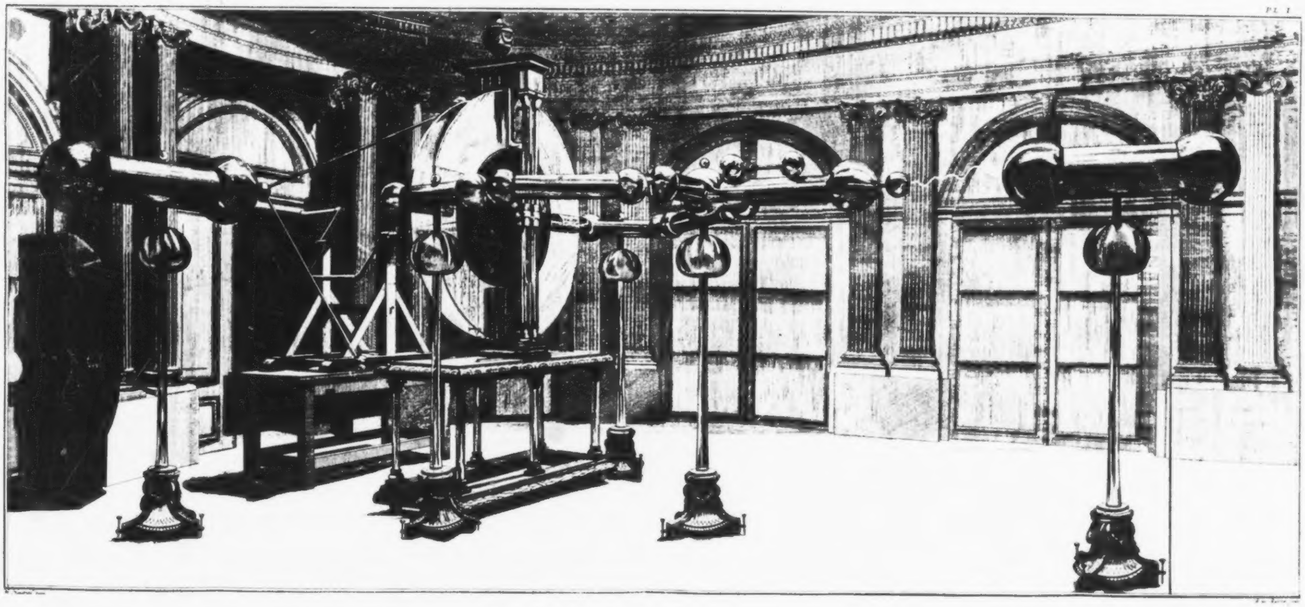
By 1750 electrical machines were far more powerful. Large glass spheres or cylinders were whirled on axles which were in turn supported by heavy wooden frames. A stuffed leather pad was substituted for the human hands. The charge on the globe was often transferred to a large metal object (such as a gun barrel) suspended nearby.

These machines were powerful enough to deliver strong electrical shocks and to produce frightening sparks; they were not toys to be handled carelessly. In 1746 Pieter van Musschenbroek, a physics professor at Leyden, reported on an accidental and very nearly fatal discovery in a letter which begins, "I wish to communicate to you a new, but terrible, experiment that I would advise you never to attempt yourself." Musschenbroek was apparently trying to catch the electrical genie in a bottle, for he had a brass wire leading from a charged gun barrel to a jar filled with water. A student, J. N. S. Allamand, was holding the jar in one hand and Musschenbroek was cranking the machine. When Allamand tried to grab the brass wire with his free hand he received the shock of his life. They repeated the experiment, this time with Allamand at the crank and Musschenbroek holding the jar. The jolt was even greater than before; Allamand must have been giving his all at the crank. Musschenbroek wrote later that he thought "...it was all up with me..." and that he would not repeat the experience even if offered the whole kingdom of France. Word of the experiment spread rapidly, and the jar came to be called a Leyden jar. Such devices for storing electric charge are now called capacitors.

Automatic Radio
20-315
15 D.C.
18 D.C.
CAN COM.
U25729

Capacitors, familiar to anyone who has looked inside a radio, are descendents of the Leyden jar. They have many different functions in modern electronics.

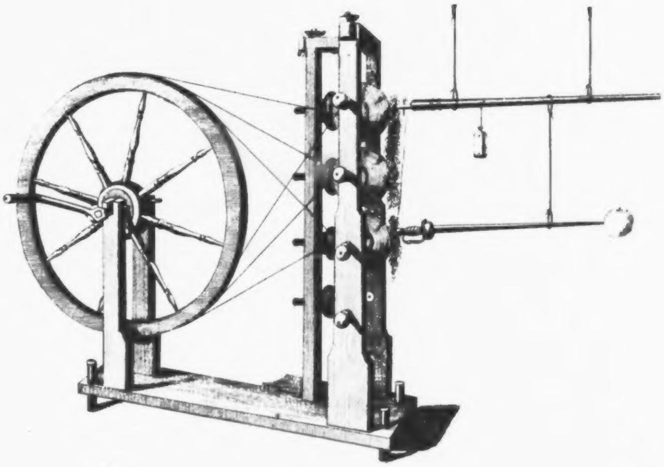
The Leyden jar came to Benjamin Franklin's attention. He performed a series of experiments with it, and published his analysis of its behavior in 1747. In these experiments Franklin showed that different kinds of charge (which we have called positive and negative) can cancel each other.

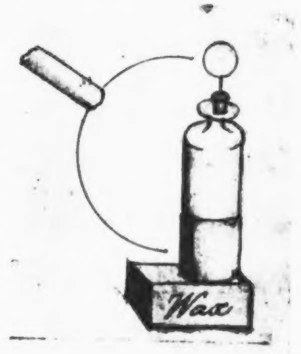


Electric Machines of the 1700's

Fig. 2
D
C
B
E
D
Fig. 1
F

The "Leyden experiment"





Franklin's drawing of a Leyden Jar. It can hold a large charge because positive charges hold negative charges on the other side of a nonconducting wall.

Because of this cancellation he concluded that the two kinds of charge were not really different.

Franklin thought that only one kind of electricity need be invoked to explain all phenomena. He considered a body to be charged positively when it had an excess of "electrical fire" and to be charged negatively when it had a deficit of it. Although this view is no longer held today, it was sufficient to account for most facts of electrostatics known in the eighteenth century.

Franklin's theory also suggested that electric charge is not created or destroyed. Charges occurring on objects are due to rearrangement of electric charges—this was a redistribution rather than a creation of "electrical fire." Similarly, positive and negative charges can cancel or neutralize each other without being destroyed. These ideas are contained in the modern principle of conservation of charge, which is taken to be a very basic law of nature as are the conservation principles of momentum and energy.

Q13 **What experimental fact led Franklin to propose a theory based on the assumption of a single type of charge?**

14.7 Electric currents.

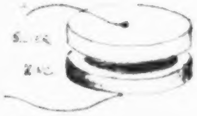
Until late in the eighteenth century, an appreciable movement of charge or electric current could be produced only by discharging a Leyden jar. Such currents last only for the instant it takes for the jar to discharge.

In 1800, Allessandro Volta discovered a much better way of producing electric currents. Volta demonstrated that the mere contact of objects is sometimes sufficient to produce an electric charge. If different metals, each held with an insulating handle, are put into contact and then separated, one will have a positive charge and the other a negative charge. Volta reasoned correctly that a much larger charge could be produced by stacking up several pieces of metal. This line of thought led him to undertake a series of experiments which led to an amazing finding, reported in a letter to the Royal Society in England in March of 1800:

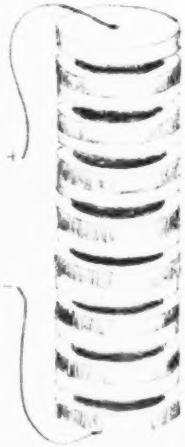
> Yes! the apparatus of which I speak, and which will doubtless astonish you, is only an assemblage of a number of good conductors of different sorts arranged in a certain way. 30, 40, 60 pieces or more of copper, or better of silver, each in contact with a piece of tin, or what is much better, of zinc, and an equal number of layers of water or some other liquid which is a better conductor than pure water, such as salt water or lye and so forth, or pieces of cardboard or of leather, etc. well soaked with these liquids....
>
> I place horizontally on a table or base one of the metallic plates, for example, one of the silver ones, and on this first plate I place a second plate of zinc;

Count Alessandro Volta (1745-1827) was given his title by Napoleon in honor of his electrical experiments. He was Professor of Physics at the University of Pavia, Italy. Volta showed that the electric effects previously observed by Luigi Galvani, in experiments with frog legs, were due to the contact of metals and not to any special kind of "animal electricity." (See the article "A Mirror for the Brain" in the Project Physics Reader 4 for an account of this controversy.)

> on this second plate I lay one of the moistened discs; then another plate of silver, followed immediately by another of zinc, on which I place again a moistened disc. I thus continue in the same way coupling a plate of silver with one of zinc, always in the same sense, that is to say, always silver below and zinc above or vice versa, according as I began, and inserting between these couples a moistened disc; I continue, I say, to form from several of these steps a column as high as can hold itself up without falling.



Voltaic cell



Voltaic pile or battery

Volta found that the discharge of his apparatus, which he called a "battery," produced an effect similar to that of the Leyden jar but more powerful. He showed that one end, or "terminal," of the battery was charged positive, and the other negative. On the basis of such evidence, Volta argued that the electricity produced by his battery was the same as the electricity produced by rubbing amber, or by friction in electrostatic machines. Today this might seem obvious, but at the time it was important to show that many phenomena such as lightning, sparks from amber and currents from a battery have a common physical basis.

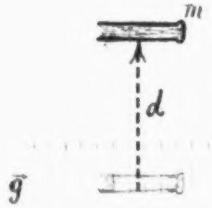
Volta's battery was important because it provided a means of producing a more or less steady current for a long period of time. Thus the properties of electric currents as well as static electric charges could be studied in the laboratory.

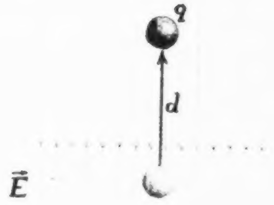
Q14 **In what ways was Volta's battery superior to a Leyden jar?**

14.8 Electric potential difference. The sparking and heating produced when the terminals of an electric battery are connected show that energy from the battery has been transformed into light, sound and heat energy. The battery converts chemical energy to electrical energy which, in turn, is changed to other forms of energy in the conducting path between the terminals. In order to understand electric currents and the way electric currents can be used to transport energy, it is necessary to understand electric potential difference. This term may be new to you, but actually you are already familiar with the idea under another name: "voltage".

A 1½-volt cell is one which has a potential difference of 1½ volts between its two terminals. (Often called a "battery," although technically a battery is a group of connected cells.)

Change in potential energy is equal to the work required to move an object frictionlessly from one position to another (Sec. 10.2). For example, the gravitational potential energy is greater when a book is on a shelf than it is when the book is on the floor; the increase in potential energy is equal to the work done raising the book from floor to shelf. This difference in potential energy depends on three factors: the mass of the book, the strength of the gravitational field, and the difference in height between the floor and the shelf.





In a similar way, the electric potential energy is changed when work is done on an electric charge in moving it from one point to another in an electric field. The magnitude of this change in potential energy can be expressed as the product of the magnitude of the charge q and a quantity called electric potential difference that depends on the electric field and the location of the two points. Electric potential difference is the ratio of the change in electric potential energy of a charge to the magnitude of the charge. In symbols,

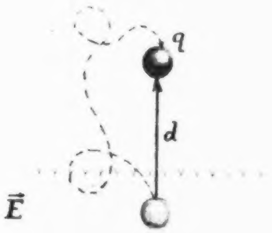
$$V = \frac{\Delta(PE)}{q}\ . \tag{14.9}$$

The symbol V is used both for "potential difference" as in Eq. 14.9, and as abbreviation for volt, the unit of potential difference (as in 1V = 1 J/coul).

The units of electric potential difference are those of energy divided by charge, or joules per coulomb.

The potential difference between two points is defined to be 1 volt if 1 joule of work is done in moving 1 coulomb of charge from one of the points to the other.

1 volt = 1 joule/coulomb.



The potential difference between two points in a steady electric field depends on the location of the points, but not on the path followed by the test charge. Thus it is possible to speak of the electric potential difference between two points, just as it is possible to speak of the difference in gravitational potential energy between two points.

Let us see how this definition is used in a simple case by calculating the potential difference between two points in an electric field, such as the electric field used in the Millikan experiment. Consider two points in a uniform electric field of magnitude E produced by oppositely charged parallel plates. The work done moving a positive charge q from one point to the other is the product of the force qE exerted on the charge, and the distance d along the field through which the charge is moved. Thus

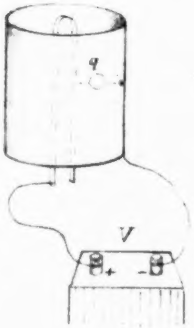
$$\Delta(PE) = qEd.$$

The electrical potential difference, defined above, is

$$V = \frac{\Delta(PE)}{q} = \frac{qEd}{q} = Ed.$$

(Note that the electric potential difference is defined in such a way that it is independent of the magnitude of the charge that is moved.)

Electric potential energy, like gravitational potential energy, can be converted into kinetic energy. A charge placed in an electric field, but free of other forces, will move so as to increase its kinetic energy at the expense of electric potential energy. (In other words, the electric force on the charge acts in such a way as to push it toward a region of lower potential energy.) A charge q, "falling" through a potential difference V, increases its kinetic energy by qV. The increase in kinetic energy is equal to the decrease of potential energy; the sum of the two remains constant.



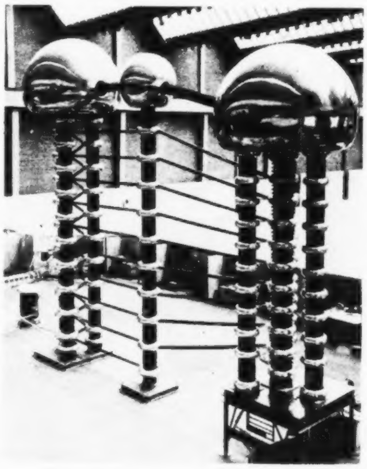
The conversion of electric potential energy to kinetic energy finds application in the electron accelerator and in the more familiar television picture tube. When moving through a potential difference of one volt, an electron with a charge of 1.6×10^{-19} coulomb increases its kinetic energy by 1.6×10^{-19} joules. This amount of energy is called an "electron volt." Energies of atomic and nuclear particles are commonly expressed as multiples of the electron volt (see Chapter 19). The electron volt (eV), or more frequently now the billion electron volt (abbreviated BeV), is also used to describe the ability of an accelerator to give kinetic energy to elementary particles.

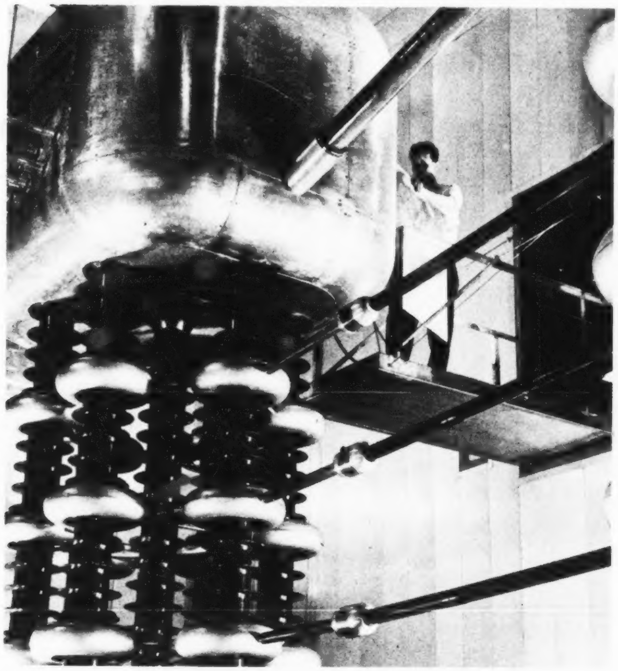
SG 14.20

Q15 How is the electric potential difference, or "voltage," between two points defined?

Q16 Does the potential difference between two points depend on the path followed in taking a charge from one to the other? Does it depend on the magnitude of the charge moved?

Q17 Is the electron volt a unit of charge, or voltage, or what?

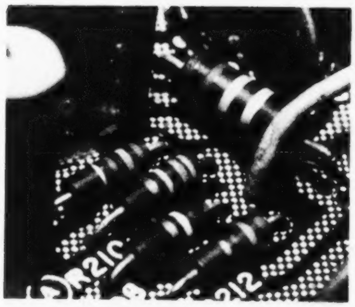




Particle accelerators come in a wide variety of shapes and sizes. They can be as common as 1000-volt oscilloscopes and 20,000-volt TV "guns" (see photos in Study Guide), or as spectacular as the ones on this page. On the left is shown part of a 750 kilovolt proton accelerator at Brookhaven National Laboratory on Long Island. Above is shown part of a 1.5 million volt electron accelerator in Basel, Switzerland. The particles from these accelerators are injected into still larger machines and there are further accelerated by repeatedly passing them across a relatively small potential difference.

14.9 Electric potential difference and current. The acceleration by an electric field of an electron in a vacuum is the simplest example of the effect of a potential difference on a charged particle. A more familiar example is electric current in a metal wire. Here the relation between motion and potential difference might seem to be more complicated, because electrons in a metal are continually interacting with the atoms of the metal. However, there is a simple relation which is approximately valid in the case of metallic conductors: the total current is proportional to the potential difference:

$$\text{current } (I) \propto \text{potential difference } (V).$$


Parts of the electric circuit in the tv set pictured on p. 42. These "resistors" have a fairly constant voltage to current ratio (the value of which is indicated by colored stripes).

This relation is called Ohm's law. It is usually written in the form

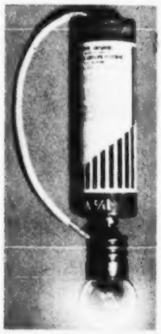
$$I = V/R \qquad (14.10)$$

where R is called the resistance. Thus Ohm's law states that the resistance of a given substance does not change appreciably with current or voltage. (It does, however, change with the temperature, length and diameter of the wire.)

Ohm's law is a good empirical approximation, but it does not have the broad applicability of more important laws such as the law of universal gravitation or Coulomb's law. We will use it mainly in connection with the discussion of electric light bulbs and power transmission in Chapter 15.

Q18 How does the current in a metallic conductor change if the potential difference between the ends of the conductor is doubled?

14.10 Electric potential difference and power. When a battery is connected in an electric circuit, chemical changes inside the battery produce an electric field which charges one terminal negative and one terminal positive. The voltage of the battery is a measure of the work per unit charge done by the electric field in moving charge through any external path from one terminal of the battery to the other. If the charge could move freely from one terminal to the other in an evacuated tube, the work done on the charge would just increase the kinetic energy of the charge. However, if the charge moves through some material, it will transfer energy to the material through collisions; some of the work will go into increasing the internal energy of the material. If, for example, the battery is forcing charges through the filament wire in a flashlight bulb, the electric work done on the charges is dissipated in heating the filament. (The hot filament radiates energy, a small fraction of which is in the form of visible light.)



Recall now that voltage (potential difference) is the amount of *work* done per unit of *charge* transferred. Also current is the number of units of *charge* transferred per unit *time*. So the product of voltage and current will then be the amount of *work* done per unit *time*:

$$V(\text{joules/coulomb}) \times I(\text{coulombs/sec}) = VI(\text{joules/sec}).$$

But work done per unit time is called *power*. The unit of power, equal to 1 joule/sec, is called a "watt." Using the definition of ampere (1 coulomb/sec) and volt (1 joule/coulomb), we can write for the power P:

$$P(\text{watts}) = V(\text{volts}) \times I(\text{amperes}). \qquad (14.11)$$

What happens to this power? As the charge moves to a lower potential, it does work against the resistance of the material and the electrical energy is converted into heat energy. If V is the voltage across some material carrying a current I, the power dissipated as heat will be $P = VI$. This can be expressed in terms of the resistance of the material by substituting IR for V:

$$\begin{aligned} P &= IR \times I \\ P &= I^2R. \end{aligned} \qquad (14.12)$$

Example: A small flashlight bulb connected to a 1.5-volt cell will have a current of about 0.1 ampere in its filament. At what rate is electric work being done to heat the filament in the bulb?

$$\begin{aligned} P &= VI \\ &= 1.5 \text{ volts} \times 0.1 \text{ amps} \\ &= 0.15 \text{ watts} \end{aligned}$$

(Only a small fraction of this power goes into the visible light energy radiated from the filament.)

SG 14.22
SG 14.23
SG 14.24
SG 14.25

Joule was the first to find experimentally that the heat produced by a current is proportional to the square of the current. This discovery was part of his series of researches on conversion of different forms of energy (see Sec. 10.8). The fact that the rate of dissipation of energy is proportional to the *square* of the current has great significance in making practical use of electric energy, as we will see in the next chapter.

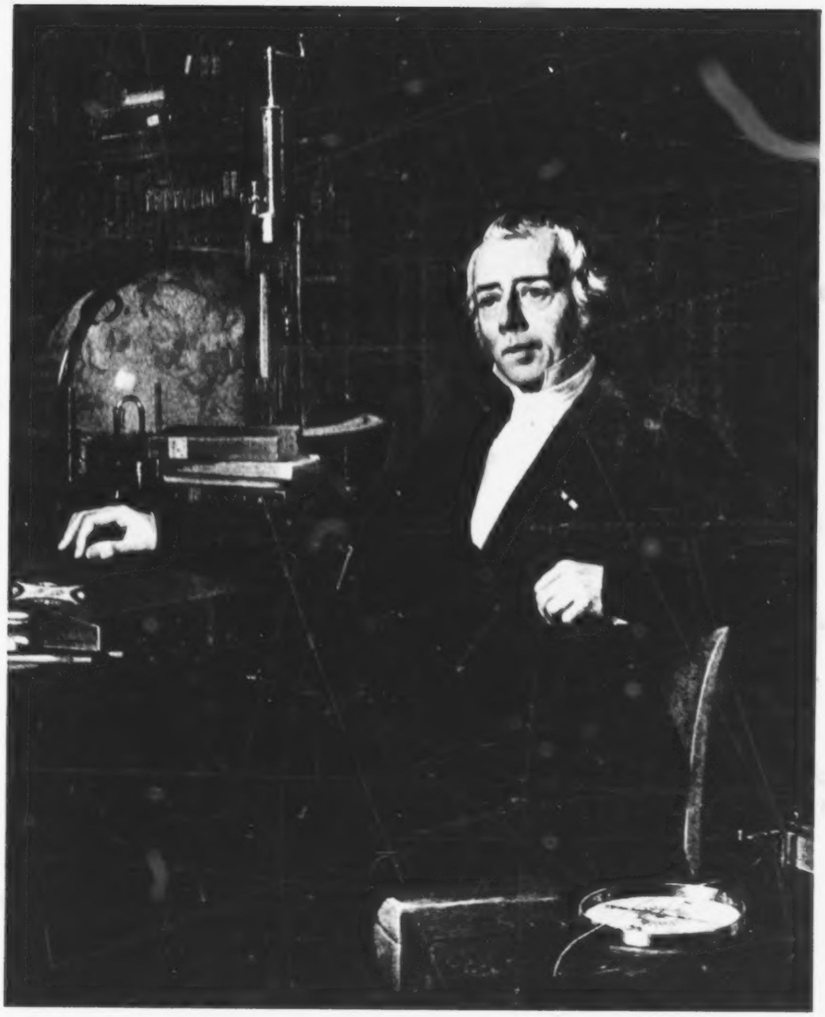
Q19 What happens to the electrical energy used to move charge in a conducting material?

Q20 How does the power dissipated as heat in a conductor change if the current in the conductor is doubled?

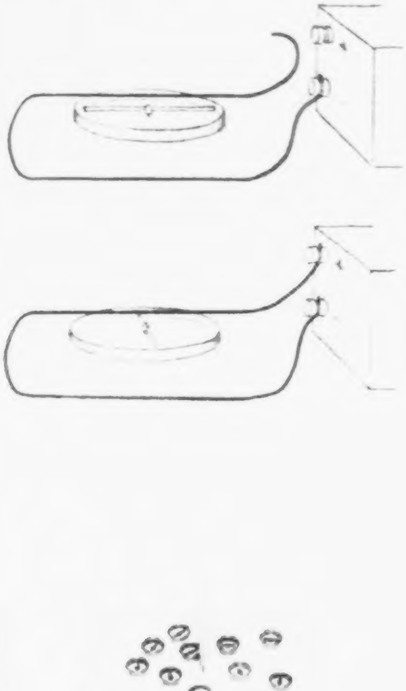
14.11 *Currents act on magnets*. Since early in the eighteenth century there were reports that lightning had changed the magnetization of compass needles and had made magnets of knives and spoons. Some believed that they had magnetized steel needles by discharging a Leyden jar through them. These reports suggested that electricity and magnetism are intimately related in some way.

None of these occurrences surprised adherents of the nature philosophy current in Europe at the start of the nineteenth century. They were convinced that all the observed forces of nature were different manifestations of a single force. Their metaphysical belief in the unity of physical

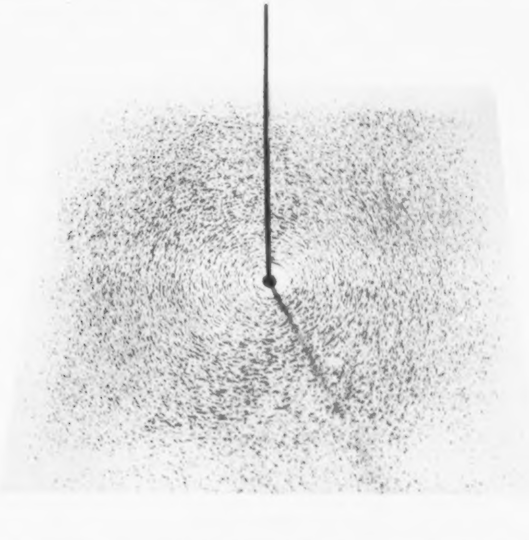
Oersted's Discovery

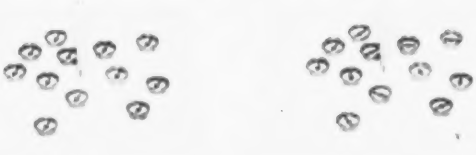


Hans Christian Oersted (1777-1851), a Danish physicist, studied the writings of the nature philosopher Schelling and wrote extensively on philosophical subjects himself. In an essay published in 1813, he predicted that a connection between electricity and magnetism would be found. In 1820 he discovered the circular magnetic field around an electric current by placing a compass under a current-carrying wire. In later years he vigorously denied the suggestion of other scientists that his discovery of electromagnetism was accidental.



To make the photograph below, a thick wire was inserted through a sheet of cardboard and tiny slivers of iron were sprinkled on the sheet. A strong current through the wire creates a magnetic field which causes the slivers to become magnetized and to line up in the direction of the field.



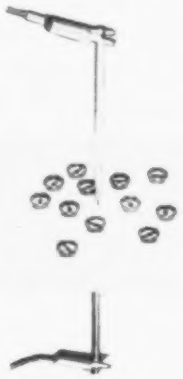


An array of tiny compasses on a sheet of cardboard placed perpendicular to a brass rod. When there is a strong current in the rod, the compass needles line up along the magnetic field of the current an indicate that the lines of force are circular around the rod.

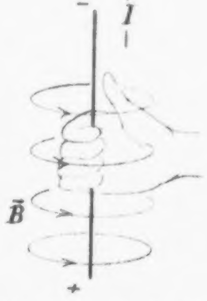
forces would, in fact, lead them to expect that electrical and magnetic forces were associated in some way.

The first concrete evidence of a connection between electricity and magnetism came in 1820, when Oersted performed a momentous series of experiments. Oersted placed a magnetic compass needle directly beneath a long horizontal conducting wire. He had placed the wire along the earth's magnetic north-south line, so that the magnetic needle was aligned parallel to the wire. When the wire was connected to the terminals of a battery, the compass needle swung to an east-west orientation—perpendicular to the wire! While charge at rest does not affect a magnet, charge in motion (a current) does exert a strange kind of "sideways" force on a magnet.

Oersted's results were the first instance in which a force was observed that did not act along a line connecting the sources of the force. The force that the current-carrying wire exerts on a magnetic pole is not along the line from the wire to the pole: the force on the pole is perpendicular to all such lines. The magnetic needle is not attracted to or repelled by the current; it is twisted sidewise by forces on its poles.



The way a current affects a compass needle certainly seemed odd. No wonder it had taken so long before anyone found the connection between electricity and magnetism. Closer examination revealed more clearly what was happening. The long straight current-carrying wire turns a small magnet so that the north-south line on the magnet is tangent to a circle that has its center at the wire and lies in a plane perpendicular to the wire. Somehow, the current produces a circular force field, not a central force field.



A useful rule: if the thumb points in the direction of the flow of charge, the fingers curl in the direction of the magnetic field. Use the right hand for positive charge flow, left hand for negative charge flow.

Compass needles are deflected in the region near a current, so we say the current produces a magnetic field there. We can get a clue to the "shape" of the magnetic field by sprinkling tiny slivers of iron which serve as tiny compass needles on a sheet of paper through which the current-carrying wire is passing. We define the direction of the magnetic field at each point to be the same as the direction of the force on the north-seeking pole of a compass needle placed at that point.

If we use the above definition, we can draw a set of magnetic "lines of force" around a bar magnet. These lines form a pictorial representation of the magnetic field. Interestingly enough, we can create almost the same "shape" of magnetic field by producing a current in a coil of wire. To show this, instead of using a long straight wire going through a hole in the paper as above, we bend the wire into a loop so that it goes through the paper in two places. The magnetic effects of the different parts of the wire on the iron slivers combine to produce a field pattern similar to that of a bar magnet.

Q21 Under what conditions can electric charges affect magnets?

Q22 What was surprising about the force a current exerted on a magnet?

Q23 How do we know that a current has a magnetic field around it?

André-Marie Ampère (1775-1836) was born in a village near Lyons, France. There was no school in the village and Ampère was entirely self-taught. His father was executed during the French Revolution, and Ampère's entire personal life seems to have been affected by his father's death. Ampère became a professor of mathematics in Paris and made important contributions to physics, mathematics, and the philosophy of science. His self-portrait is reproduced above.

14.12 Currents act on currents. Oersted's discovery opened up an exciting new subject of research. Soon, scores of people in laboratories throughout Europe and America began intensive studies on the magnetic effects of electric currents. The work of Andre-Marie Ampère (1775-1836) stands out among all the rest. Ampère came to be called the "Newton of electricity" by James Clerk Maxwell, who some decades later was to construct a complete theory of electricity and magnetism. Ampère's work is filled with elegant mathematics, which we cannot detail. But we can trace some of his ideas and review some of his experiments.

Ampère's thoughts began racing forward as soon as he heard Oersted's news. He began with a line of thought somewhat as follows: since magnets exert forces on each other, and since magnets and currents also exert forces on each other, can it be that currents exert forces on other currents? Although it is tempting to leap forward with a reply, the answer is not obvious. Ampère recognized the need to let experiment provide the answer. He wrote:

> When...M. Oersted discovered the action which a current exercises on a magnet, one might certainly have suspected the existence of a mutual action between two circuits carrying currents; but this was not a necessary consequence; for a bar of soft iron also acts on a magnetised needle, although there is not mutual action between two bars of soft iron.

And so Ampère put his hunch to the test. On September 30, 1820, within a week after word of Oersted's work reached France, Ampère reported to the French Academy of Science that he had found that two current-carrying wires exert forces on each other.

Ampère made a thorough study of the forces between currents, and how they depend on the distance between the wires and their relative orientations as well as on the amount of

Replica of Ampère's current balance.

current. In the laboratory you can repeat some of these experiments and work out the force law. We will not need to go into the quantitative details here, except to note that the force between currents is now used to define the unit of current, which is called the ampere (as mentioned in Sec. 14.3). One ampere is the amount of current in each of two long straight parallel wires, one meter apart, which causes a force of 2×10^{-7} newtons on each meter of wire.

(The numerical factor of 2×10^{-7} was chosen, somewhat arbitrarily, in order to get a unit of convenient size for practical use.)

Q24 What was Ampère's hunch?

Electrical units (summary)

The ampere is the fourth fundamental unit in the so-called MKSA system (meter, kilogram, second, ampere) which is now widely used by physicists.

The coulomb is defined as the amount of charge that flows in one second, when the current is 1 ampere.

The volt is defined as the potential difference between two points such that 1 joule of work is done in moving 1 coulomb of charge between those points.

The watt is defined as the amount of energy flow per second (or work done per second, or "power") which corresponds to 1 joule per second. Thus a current of 1 ampere due to a potential difference of 1 volt corresponds to 1 watt of power.

The kilowatt is equal to 1000 watts.

The kilowatt-hour is the amount of work done when one kilowatt of power is used for one hour. It is equal to 3,600,000 joules (1000 joules/sec × 3600 sec).

The ohm is defined as the resistance of a material which allows a current of just 1 ampere if the potential difference is 1 volt.

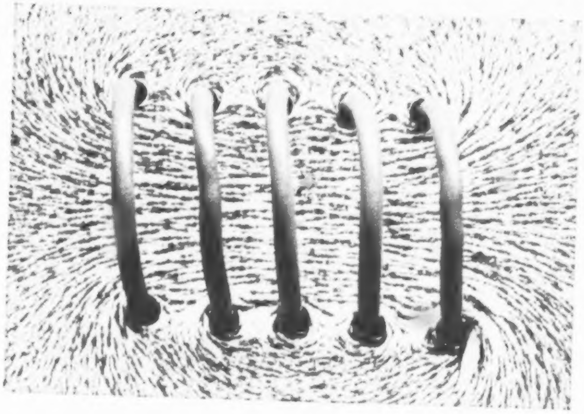
14.13 Magnetic fields and moving charges. In the last two sections we discussed the interactions of currents with magnets and with each other. The analysis of these phenomena is greatly simplified by the use of the concept of magnetic field.

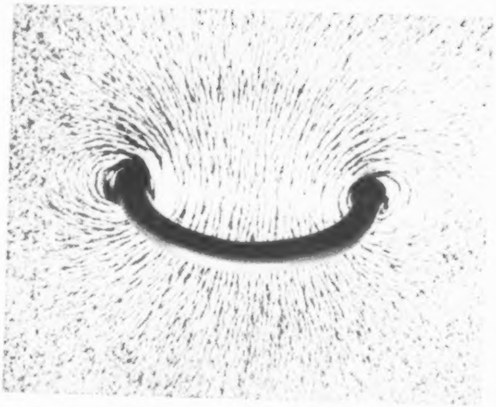
In modern physics the magnetic field strength is given the symbol $\vec{B}$, and is defined in terms of the force exerted on a charge moving through the magnetic field.

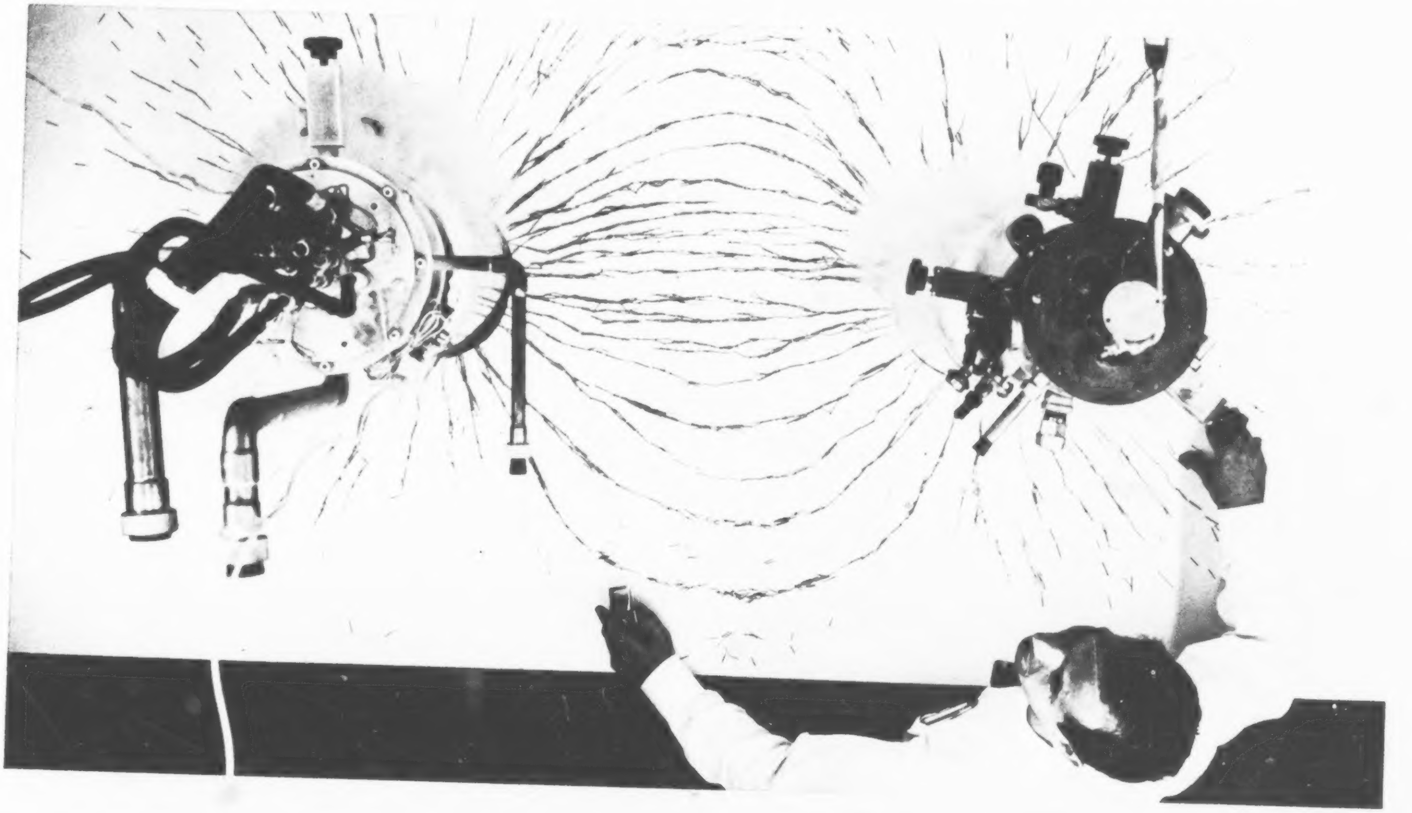
Electrically charged bodies exert forces on each other. When the charged bodies are at rest, we say that the forces are "electric" forces and imagine "electric fields" which are responsible for them. When the charged bodies are moving, new forces appear in addition to the electric forces. We call these new forces "magnetic" and attribute them to "magnetic fields."

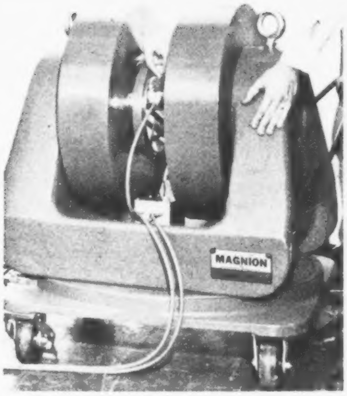
The magnetic interaction of charged bodies is not as simple as the electric interaction, since it depends on the speeds and relative directions of motion of the bodies as well as their distance. As we saw in the description of Oersted's experiment, the direction of the force exerted by a current

The diagrams at the right represent the magnetic field of a current in a loop of wire. In the first diagram, some lines of force due to opposite sides of the loops have been drawn separately. One example is given of how the two fields add at point P. Some lines of force for the total field are drawn in the second diagram. Below at the right is a photograph of iron filings in the magnetic field of an actual current loop. Below at the left is the field of a series of coils, or helix.

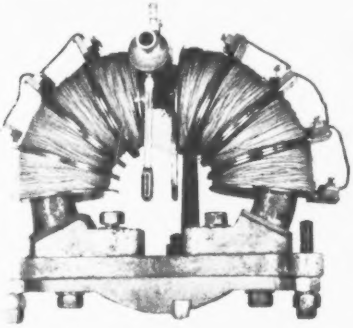




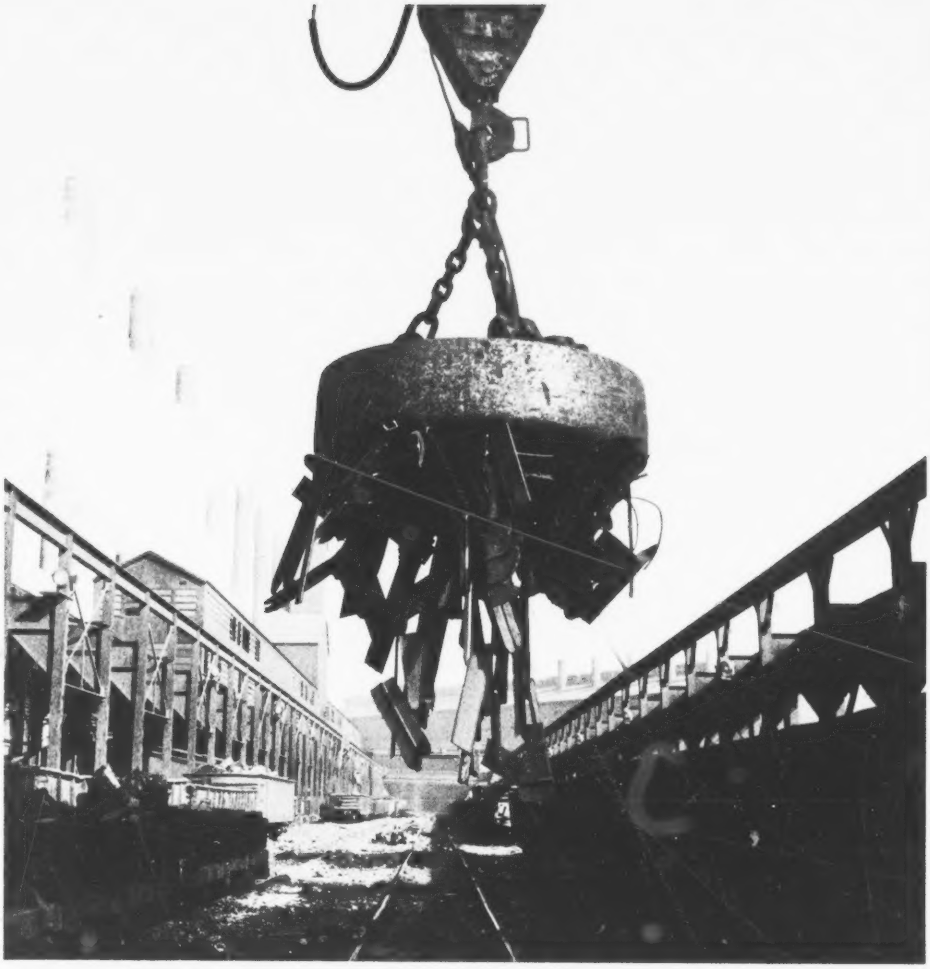




A modern electromagnet used in research when strong uniform fields are required.

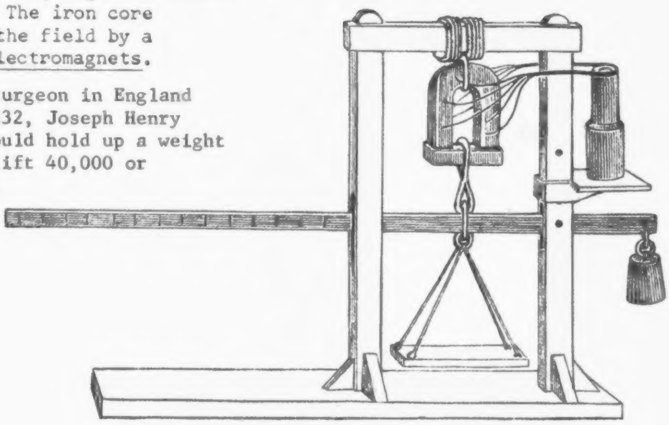


This electromagnet was used early in this century to deflect a beam of charged atoms. It appears again in Unit 6.

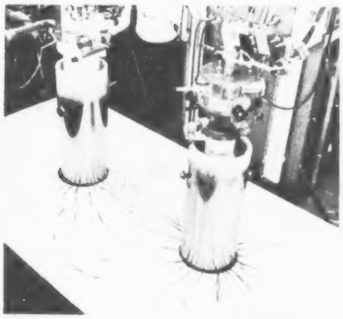


In many applications, from doorbells to cyclotrons, magnetic fields are produced by coils of wire around iron cores. The iron core becomes magnetized and increases the strength of the field by a factor of 10^2 or 10^3. Such devices are called electromagnets.

The first electromagnet, invented by William Sturgeon in England in 1824, could lift a weight of nine pounds. In 1832, Joseph Henry constructed an electromagnet at Princeton which could hold up a weight of 3,600 pounds. Modern electromagnets which can lift 40,000 or 50,000 pounds of iron are widely used in industry.

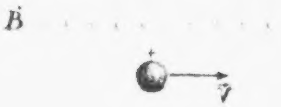


Henry's electromagnet. From American Journal of Science, 1831.

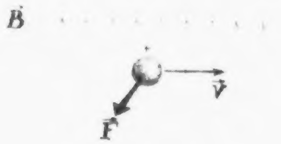


In the two pictures at the left, iron nails line up in a strong magnetic field produced by large currents in superconducting coils, kept at 4° above absolute zero by liquid helium.

on a magnet is perpendicular both to the direction of the current and to the line between the magnet and current.

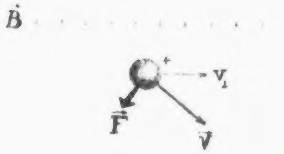


Suppose we have a magnetic field $\vec{B}$ which may be produced either by a magnet or a current, and study how this field acts on a moving charge. The force on the charge depends on three quantities: the magnitude of the charge, the velocity of the charge and the strength of the field. If the charge is moving in a direction perpendicular to the field, the magnitude of the force is proportional to each of these quantities:

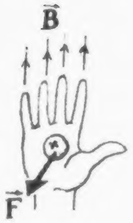


$$F \propto qvB.$$

If the charge is moving in a direction parallel to $\vec{B}$, there is no force. For other directions of motion, the force is proportional to the component of the velocity perpendicular to the field direction, $v_{\perp}$. The direction of the force is always perpendicular both to the direction of the field and to the direction of motion of the charge.



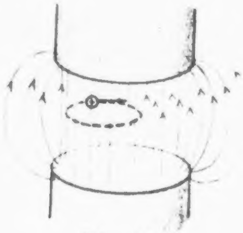
The force exerted by a magnetic field on a moving charged particle can be used to define the unit of magnetic field, by taking the proportionality constant equal to one. This definition will be convenient here since we will be mainly concerned with magnetic fields as they interact with moving charges (rather than with forces between magnets). In the case when $\vec{B}$ and $\vec{v}$ are at right angles to each other, the magnitude of the force becomes



A useful rule: if your fingers point along $\vec{B}$, and your thumb along $\vec{v}$, $\vec{F}$ will be in the direction your palm would push. For pos. charges use the right hand, and for neg. use the left hand.

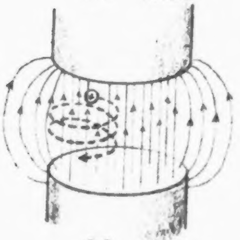
$$F = qvB. \tag{14.13}$$

The path of a charged body in a magnetic field. The magnetic force on a moving charged body is always "off to the side," that is, perpendicular to its direction of motion. Therefore, the magnetic force does not change the speed of the charged body, but it does change its velocity. If a charged body is moving exactly perpendicular to a uniform magnetic field, there will be a constant sideways push and the body will move along a circular path.



SG 14.29
SG 14.30

What happens if the charged body's velocity has some component along the direction of the field but is not exactly parallel to it? The body will still be deflected into a curved path, but the components of its motion along the field will continue undisturbed; so the particle will trace out a coiled path (see sketch). If the body moves directly along the direction of the field or directly against it, there is no force.



SG 14.31

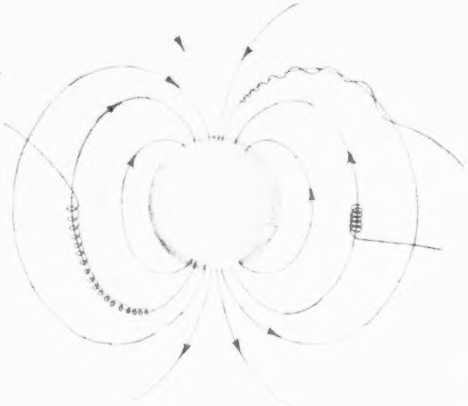
Some important examples of the deflection of charged particles by magnetic fields will be discussed in Units 5 and 6.

Here we will mention one very important example of the "coiled" motion: the Van Allen radiation belts. A stream of charged particles, mainly from the sun but also from outer space, continually sweeps past the earth. Many of these particles are deflected into spiral paths by the magnetic field of the earth, and are subsequently "trapped." The extensive zones containing the rapidly moving trapped particles are called the Van Allen belts. Some of the particles which escape from these radiation zones are deflected toward the earth's magnetic poles where they hit the atmosphere and cause the aurora ("northern lights" and "southern lights").

James A. Van Allen (b. 1914) is an Iowa-born physicist who heads the group that designed the instruments carried by the first American satellite, Explorer I. The zones of high energy particles detected by these instruments are discussed in an article by Van Allen, "Radiation Belts Around the Earth" in Project Physics Reader 4.

So far we have been discussing the interaction between currents and magnets and between magnetic fields and charged particles. These interactions have important consequences for society as well as for physics, as we shall see in the next chapter.

SG 14.32

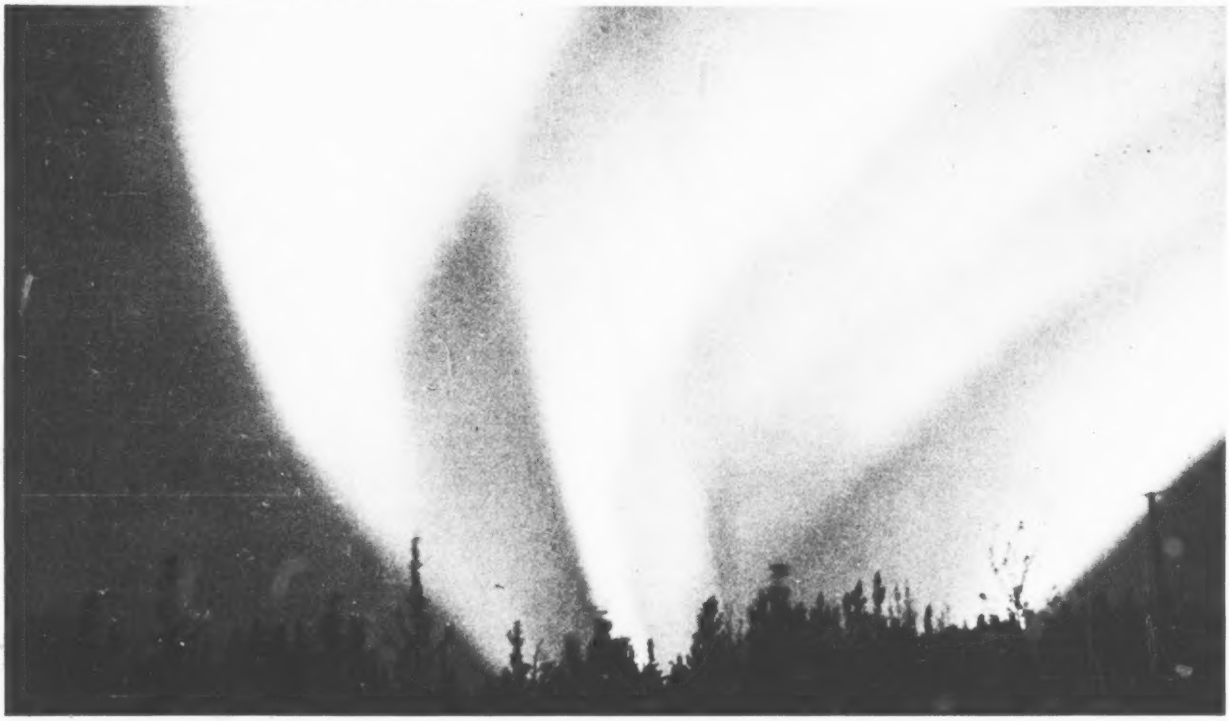


Q25 Which of the following affect the magnitude of the magnetic force on a moving charged particle?

a) the component of the velocity parallel to the field
b) the component of the velocity perpendicular to the field
c) the magnetic field $\vec{B}$
d) the magnitude of the charge
e) the sign of the charge

Q26 Which of the items in the preceding question affect the direction of the magnetic force on the charged particle?

Q27 Why does the magnetic force on a moving charged particle not change the speed of the particle?



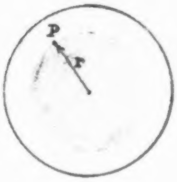
14.1 How much must you alter the distance between two charged objects in order to keep the force on them constant if you

a) triple the net charge on each?
b) halve the net charge on each?
c) double the net charge on one and halve the net charge on the other?

14.2 How far apart in air must two charged spheres be placed, each having a net charge of 1 coulomb, so that the force on them is 1 newton?

14.3 If electrostatic induction doesn't involve the addition or subtraction of charged particles, but instead is just the separation, or redistribution, of charged particles, how can you explain the fact that attraction results from induction?

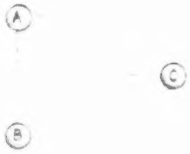
14.4 An aluminum-painted ping-pong ball hanging by a nylon thread from a ring stand is touched with a finger to remove any slight charge it may have had. Then a negatively charged rod is brought up close to but not touching the ball. While the rod is held there the ball is momentarily touched with a finger; then the rod is removed. Does the ball now have a net charge? If you think it has, make a few simple sketches to show how it became charged, indicating clearly what kind of charge it has been left with.



14.5

a) Calculate the strength of the gravitational field of the moon at a point on its surface. The mass of the moon is 7.3×10^{22} kg and its radius is 1.74×10^6 m.
b) Calculate the gravitational field at a point near the surface of a small but extremely dense star, LP357-186, whose radius is 1.5×10^6 m and whose density is 10^{22} kg/m^3.
c) The gravitational field of a uniform spherical shell is zero inside the shell. Use this principle together with Newton's gravitational force law and the formula for the volume of a sphere ($4/3\ \pi\ r^3$) to find out how the gravitational field at a point P inside a planet depends on the distance of P from the center. (Assume the planet's density is uniform throughout.)

14.6 We speak of an electric field exerting a force on a charged particle placed in the field. What has to be true about this situation in view of the fact that Newton's third law holds in this case, too?

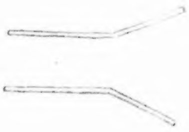


14.7 The three spheres A, B and C are fixed in the positions shown. Determine the direction of the net electrical force on sphere C which is positively charged if

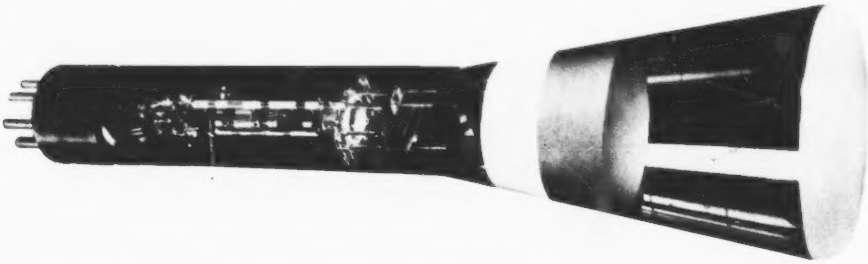
a) spheres A and B carry equal positive charges.
b) spheres A and B have charges of equal magnitude but the charge on B is negative, and A is positive.

14.8 There is an electric field strength at the earth's surface of about 100 N/coul, directed downward.

a) What is the total charge of the earth? (As Newton showed for gravitational forces, the field of a uniform sphere can be calculated by assuming all of the charge is concentrated at the center.)
b) Actually, because the earth is a conductor, most of the charge is on the surface. What, roughly, is the average amount of charge per square meter of surface? Does this seem large or small, compared to familiar static charges like those on combs, etc.?



14.9 In oscilloscope tubes, a beam of electrons is deflected by two pairs of oppositely charged plates. Each pair of plates, as can be seen in the photograph on the next page, is shaped something like the sketch in the margin. Sketch in roughly what you think the electric field between a pair of such plates would be like.



14.10 Is air friction on the oildrop a help or a hindrance in the experiment described for measurement of the charge of the electron? Explain your answer briefly.

14.11 The magnitude of the electron charge is 1.6×10^{-19} coulomb. How many electrons are required to make 1 coulomb of charge?

14.12 Calculate the ratio of the electrostatic force to the gravitational force between two electrons a distance of 10^{-10} meter apart. (The mass of the electron is approximately 10^{-30} kg; recall that $G = 6.7 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2$.)

14.13 Because electrical forces are similar in some respects to gravitational forces, it is reasonable to imagine a charged particle, such as the electron, moving in an orbit around another charged particle. Then, just as the earth is a "gravitational satellite" of the sun, the electron would be an "electric satellite" of some positively charged particle with a mass so large compared to the electron that it can be assumed to be stationary. Suppose the particle has a charge equal in magnitude to the charge of the electron, and that the electron moves around it in a circular orbit.

a) The centripetal force acting on the moving electron is provided by the electrical force between the electron and positively charged particle. Write an equation representing this statement, and from this equation derive another equation that shows how the kinetic energy of the electron is related to its distance from the positively charged particle.

b) Calculate what the kinetic energy of the electron would be if the radius of its orbit were 10^{-10} meters.*

c) What would be the speed of the electron if it had the kinetic energy you calculated in part (b)? (The mass of the electron is approximately 10^{-30} kg.)

*The value given here, as perhaps you suspect, is appropriate to an electron circling an atomic nucleus (as will be discussed in detail in Unit 5).

14.14 A hard-rubber or plastic comb stroked through the hair can often be shown to be charged. Why does a metal comb not readily show a net charge produced by combing or rubbing?

14.15 What is the potential difference between two points if 6×10^{-4} joules of work were done against electric forces in moving 2×10^{-5} coulombs of charge from one point to the other?

14.16 If there is no potential difference between any points in a region, what must be true of the electric field in that region?

14.17 Electric field intensity can be measured in either of two equivalent units: newtons-per-coulomb and volts-per-meter. Using the definitions of volt and joule, show that N/coul is actually the same as V/m. Can you explain the equivalence in words?

14.18 If the distance between the surfaces of two conducting spheres is about 1 cm, an electric potential difference of about 30,000 volts between them is required to produce a spark.

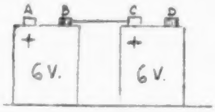
a) What is the minimum electric field strength (in the gap between the surfaces) necessary to cause sparking?

b) The gap between the two electrodes in an automobile sparkplug is about 1 mm (39 thousandths of an inch). If the voltage produced across them by the ignition coil is about 10,000 volts, what is the electric field strength in the gap?

14.19 An electric battery "pumps" charges onto its terminals until the electric potential difference between the terminals reaches a certain value; usually the value is very close to the voltage marked on the battery. What would happen if we connected two or more batteries in series?

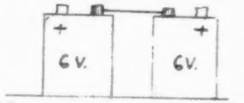
For example, the battery on the right below maintains terminal C at a potential level 6 volts higher than terminal D. The battery on the left maintains terminal A at a potential 6 volts higher than terminal B. If we connect B to C with a good conductor, so that B and C are at the same potential level, what is the potential difference between A and D?

a)

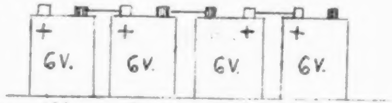


What would the potential difference be between the extreme left and right terminals in the following set-ups?

(b)



(c)



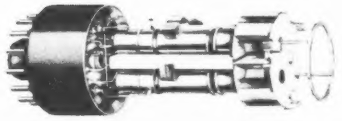
14.20
a) What kinetic energy will an electron gain in an evacuated tube if it is accelerated through a potential difference of 100 volts. State your answer in electron volts and also in joules.
b) What speed will it acquire due to the acceleration? (The mass of the electron is 10^{-30} kg.)

14.21 Suppose various metallic resistors are connected to a battery and to a current meter. The following table gives two of three quantities related by Ohm's law for three separate cases. Complete the table.

If a potential difference of 1 volt results in a current of 1 ampere, the resistance is defined to be 1 ohm.

	Voltage	Current	Resistance
a)	2 volts		0.5 ohms
b)	10 volts	2 amps	
c)		3 amps	5 ohms

14.22 The electric field at the earth's surface can increase to about 10^4 volts/meter under thunder clouds.
a) About how large a potential difference between ground and cloud does that imply?
b) A set of lightning strokes can transfer as much as 50 coulombs of charge. Roughly how much energy would be released in such a discharge?



Three "guns" are mounted side by side to produce three charge beams in a color tv tube. Charges emitted from hot wires just inside the left end of the guns are accelerated from one cylindrical electrode to the next and emerge from the guns toward the screen with almost exactly the same energy.

14.23 "Physics International's B^2 Pulsed Radiation Facility is now producing the world's most intense electron beam (40,000 amps/4 MeV) as a routine operation. With this beam PI can precisely deposit upwards of 5,000 joules of energy in 30 nanoseconds." (Physics Today, Dec. 1966)

The "4 MeV" means that the charges in the beam have an energy that would result from being accelerated across a potential difference of 4 million volts. A "nanosecond" is a billionth of a second. Are these published values consistent with regard to the power of the beam?

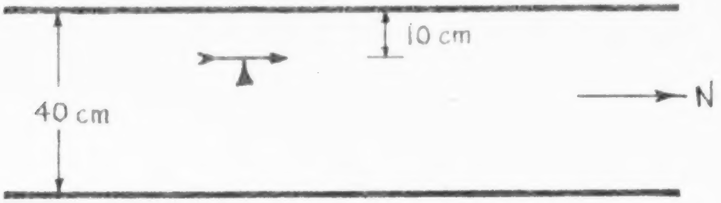
14.24 If the beam in a TV tube constitutes a current on the order of 10^{-3} amps, roughly what is the power of the picture?

14.25 Calculate the power dissipated for each of the three parts of question 14.21.

14.26 A student who wished to show the magnetic effect of a current on a pocket compass, slowly slid the compass along the table top toward a wire lying on the table and carrying a constant current. He was surprised and puzzled by the lack of any noticeable turning effect! How would you explain to him what is wrong with his experiment, or with his expectation of the outcome?

14.27 The sketch shows two long, parallel wires, lying in a vertical north-south plane (the view here is toward the west). A horizontal compass is located 10 cm below the upper wire. With no current in the wires, the needle points N. With 1 amp in the upper wire, the needle points NW.

What is the direction of this one ampere current?



14.28 What current (magnitude and direction) in the lower wire would restore the compass needle to its original position? (Use the results of Experiments 35 and 36.)

14.29 The magnetic force on a charged particle moving perpendicularly to a uniform magnetic field is directed toward a single point—the center of the circular path the particle will follow.

a) Knowing that the magnetic force (given by qvB) provides the centripetal force (given by mv^2/R), show that the radius of the circle is directly proportional to the momentum of the particle.

b) What information would you need to determine the radio of the particle's charge to its mass?

14.30 By referring to the information given in the last problem, find an equation for the period of the circular path.

14.31 In the margin is a sketch of a positively charged particle moving in a very non-uniform magnetic field.

a) Show mathematically that the radius of the spiral path will be smaller where the field strength is greater.

b) Use the right hand rule to show that the direction of the magnetic force is such as to partially oppose the movement of the particle into the region of stronger field.

14.32 If the energy of charged particles approaching the earth is very great, they will not be trapped in the Van Allen belts, but just deflected, continuing on past or into the earth. The direction of the earth's magnetic field is toward its north end. If you set up a detector for positively charged particles, would you expect to detect more particles by directing it slightly toward the east or slightly toward the west?

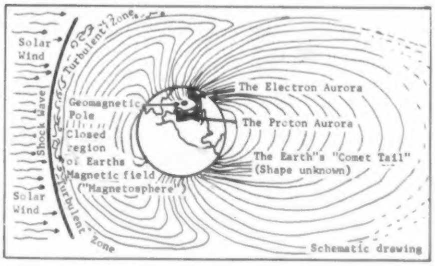


Diagram of the magnetic field of the earth distorted by a "wind" of electric charges streaming out from the sun. (New York Times, September 11, 1966)

Chapter 15 Faraday and the Electrical Age

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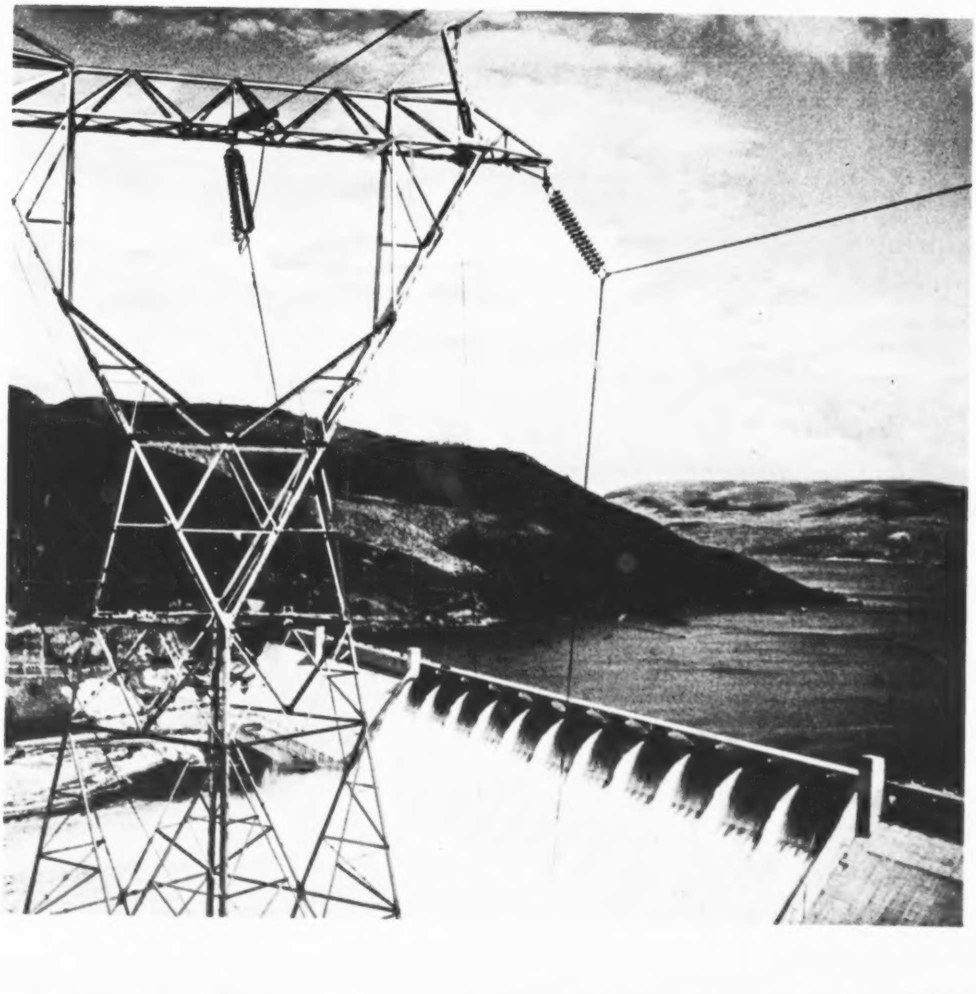
*Pages 95-99 adapted from H. I. Sharlin's book, *The Making of the Electrical Age*.



15.1 The problem: getting energy from one place to another. In Chapter 10 we discussed the development of the steam engine, in the eighteenth and nineteenth centuries, which enabled Europe and America to make use of the vast stores of energy contained in coal, wood and oil. By burning fuel one can convert chemical energy into heat energy. Then, by using this heat energy to make steam and letting the steam expand against a piston or a turbine vane, one can get mechanical energy. In this way one can use the steam engine to move large weights or turn cranks to run machinery.

But steam engines suffered from a major defect: the mechanical energy was available only at the place where the steam engine was located, and practical steam engines had to be big, hot and dirty. In order to use machines run by steam engines, people had to crowd together in factories. It was possible to use steam engines for transportation by making locomotives, which were astonishing and powerful but also limited by their size and weight, not to speak of soot.

A better power system would have one central power plant from which energy could be sent out, for use at a distance, by machines of any desired size and power at the most useful locations.

After Volta's invention of the battery (Chapter 14), many scientists guessed that electricity might provide a means of transporting energy and running machines. But batteries quickly lost their power and provided only a very feeble current. A better way of generating electrical currents was needed. When this was found, it changed the whole shape of life at home and in factories, and it changed also the very appearance of cities and landscapes.

In this chapter we will see how discoveries in basic physics gave rise to new technologies—technologies which have revolutionized modern civilization.

15.2 Clue to the solution: electromagnetism. The first clue came from Oersted's discovery that a magnetic needle is deflected by a current. Suppose we make the very reasonable assumption that Newton's third law applies to electrical and magnetic forces. Then if a current can exert a force on a magnet, we expect that a magnet should also exert a force on a current. Going beyond what Newton's third law says to a more general idea of symmetry, we might even speculate that a magnet can somehow produce a current.

Scientists and inventors in both Europe and America quickly realized that there were important—and perhaps profitable—

discoveries waiting to be made in electromagnetism. Within a few months after the news of Oersted's discovery reached Paris, the French physicists Biot, Savart and Ampère had begun a program of quantitative research on the interactions of electricity and magnetism. (Some of their results were mentioned in Sec. 14.8.) In Germany, Seebeck found that a current could magnetize a steel needle. In England, Davy and Wollaston tried unsuccessfully to make a wire revolve around its own axis by bringing a magnet close to it. Other experiments and speculations on electromagnetism, too numerous to mention, were soon reported in the scientific journals. Yet the one crucial discovery—the generation of a continuous electric current—still eluded these eminent and brilliant men.

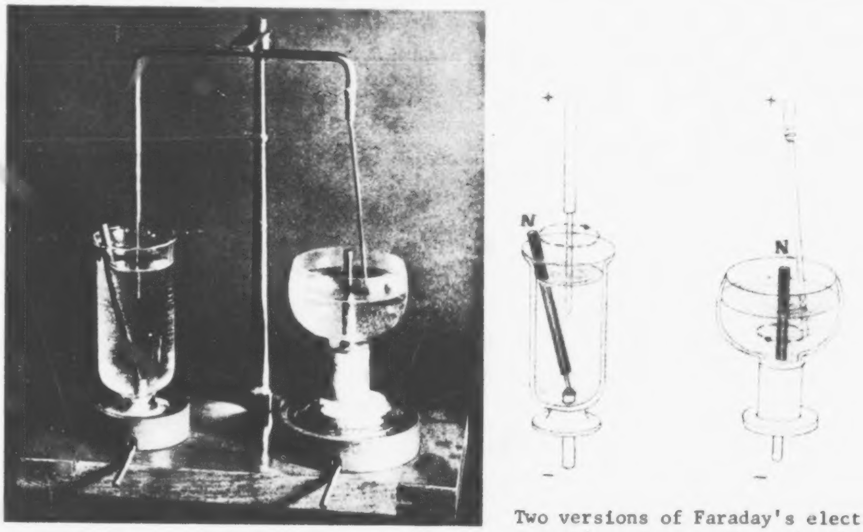
15.3 *Faraday's early work on electricity and lines of force.* A valuable function of scientific journals is to provide for their readers comprehensive survey articles on recent advances in science, as well as the usual terse announcements of the technical details of discoveries. The need for a review article is especially great after a large burst of activity such as that which followed Oersted's discovery of electromagnetism in 1820.

In 1821 the editor of the British journal *Annals of Philosophy* asked Michael Faraday to undertake a historical survey of the experiments and theories of electromagnetism which had appeared in the previous year. Faraday, who was at that time an assistant to the well-known chemist Humphry Davy, did not yet have a reputation in science but was eager to learn all he could. Faraday agreed to accept the assignment, but soon found that he could not limit himself to merely reporting what others had done. He had to repeat the experiments in his own laboratory, and, not being satisfied with the theoretical explanations proposed by other physicists, started to work out his own theories and plans for further experiments. Before long Faraday, who had originally been apprenticed to a bookbinder and had no formal training in science or mathematics, had launched a series of researches in electricity that was to make him one of the most famous physicists of his time.

Faraday's first discovery in electromagnetism was made on September 3, 1821. Repeating Oersted's experiment by holding a compass needle at various places around a current-carrying wire, Faraday realized that the force exerted by the current on the magnet is *circular* in nature. As he expressed it a few years later, the wire is surrounded by circular *lines of*

force, so that a magnetic pole which is free to move will be pushed in a circle around a fixed wire (see the discussion of lines of force in Chapter 14). Faraday immediately constructed an "electromagnetic rotator" based on this idea. It worked: Faraday had invented the first electric motor!

Faraday also designed an arrangement in which the magnet was fixed and the current-carrying wire rotated around it. (If a current can exert a force on a magnet, a magnet should be able to exert an equal and opposite force on a current, according to Newton's third law.) As in many other cases, Faraday was guided by the idea that for every effect of electricity on magnetism, there must be a converse effect of magnetism on electricity. But it was not always so obvious what form the converse effect would take.



Two versions of Faraday's electromagnetic rotator. In each, the cup was filled with mercury so that a large electric current can be passed between the base and overhead support. At the left, the north end of a bar magnet revolves along the circular electric lines of force surrounding the current. At the right, the rod carrying the current revolves around the bar magnet—moving always perpendicular to the magnetic lines of force.

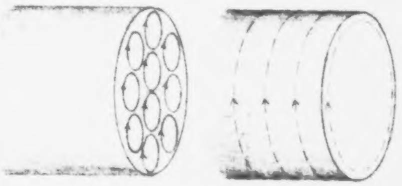
After Faraday's paper describing electromagnetic rotation was published, Ampère criticized it on theoretical grounds. To understand the reasons for this criticism (and for the failure of many contemporary physicists to accept Faraday's theories) we must recall that the Newtonian viewpoint was still dominant in European science at this time. Not only did almost all scientists accept Newton's laws of motion as the basis for mechanics, they also believed that all forces in nature must somehow be similar to the Newtonian gravitational force. That is, forces must act directly between particles of matter in a direction along the line between the centers of the particles. They need not be attractive forces in all cases, and they need not even be inversely proportional to the square of the distance between the particles. Newton himself had proposed other kinds of forces; for example, repulsive forces inversely proportional to the distance between neighboring particles in a gas (see Chapter 11). However, no one had ever supposed that forces could act in any direction other than the direction along the line between the particles. Yet here was Faraday proposing a "circular" force; that is, a force exerted by a current on a magnet which acted in a direction at right angles to the line between them.

Faraday, despite his ignorance of Newtonian mathematical physics, seemed to have the experimental facts on his side. Anyone could see that the magnet did actually rotate around the current (or the current around the magnet). Why not simply assume that a circular force causes this motion?

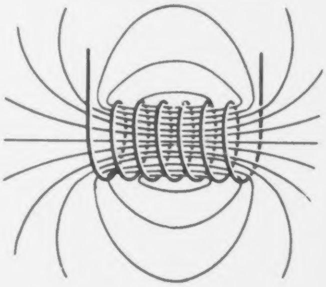
Ampère could not accept the idea of a circular force. Instead, he argued that all the interactions of electricity and magnetism can be reduced theoretically to interactions between individual parts, or "elements," of current-carrying wires. Just as in Newton's theory of gravitational force, the forces between current elements must act in the direction along the line between the elements.

How could such a theory explain the forces exerted by magnets, or on magnets? Ampère had noticed that a current would orient iron filings into a pattern in much the same way as would a magnet. In particular, a long wire wrapped into a tight coil, or "helix," had all the properties of a bar magnet, the coil's "poles" being at its ends. Ampère therefore made the bold assumption that the attractive and repulsive forces between magnets are the result of electric currents circulating within the magnets themselves. In this way he could treat a magnet as if it were made up of current elements. What seemed to be a circular force was really, according to Ampère, the total effect produced by a large number of direct forces between current elements.

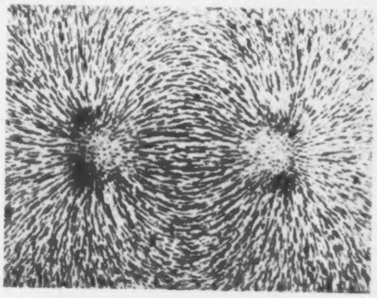
Ampère proposed that a magnet consisted of a large number of microscopic current loops. These currents cancelled each other everywhere but at the surface, so that the net effect was the same as a coil of wire.



Field of a wire coil



Field of a bar magnet



Ampère preferred his explanation of electromagnetic interactions because it could be expressed mathematically with the equations familiar in Newtonian physics. Faraday, on the other hand, did not understand much mathematics, but he did have an amazing intuitive feeling for physical phenomena. In most instances where mathematics has conflicted with intuition in the history of physics, mathematics has eventually won out. (The success of Galileo and Newton in developing the laws of motion is a good example.) But in this case, Faraday's nonmathematical approach gained at least a temporary victory for intuition. Faraday's idea of electric and magnetic "lines of force" led him to make important discoveries in electromagnetism—discoveries that the mathematical physicists were prevented from making by their Newtonian prejudices. Not until 1855, when another brilliant mathematical physicist, James Clerk Maxwell, took the trouble to figure out what Faraday meant by a line of force, was it possible to see how Faraday's ideas might be incorporated into the framework of Newtonian physics. (We will discuss this work of Maxwell on the "electromagnetic field" in Chapter 16.)

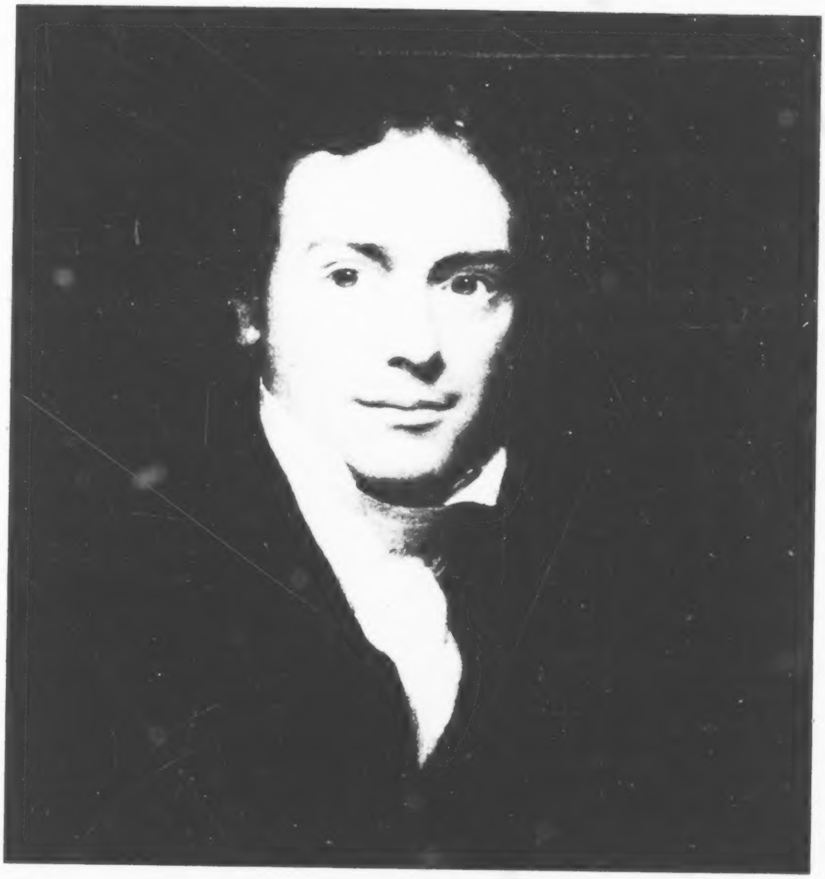
Q1 Why is the magnetic pole of Faraday's "electromagnetic rotator" pushed in a circle around a fixed wire?

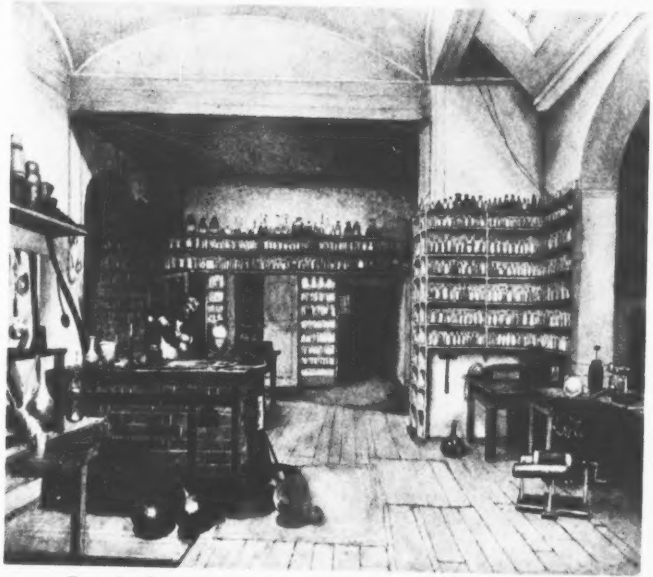
Q2 What did Ampère assume caused the forces between magnets?

15.4 The discovery of electromagnetic induction. Armed with his "lines of force" picture for understanding electric and magnetic fields, Faraday joined in the search for a way of producing currents by magnetism. Scattered through his diary in the years after 1824 are many descriptions of such experiments. Each report ended with a note: "exhibited no action" or "no effect."

Finally, in 1831, came the breakthrough. Like many discoveries which have been preceded by a period of preliminary research and discussion among scientists, this one was made almost simultaneously by two scientists working independently in different countries. Faraday was not quite the first to produce electricity from magnetism; that was actually done first by an American scientist, Joseph Henry. Henry was teaching mathematics and philosophy at an academy in Albany, New York, at the time. (Shortly thereafter he was appointed Professor of Natural Philosophy at Princeton.) Unfortunately for the reputation of American science, teachers at the Albany Academy were expected to spend all their time on teaching and administrative duties, with no time left for research. Henry had hardly any opportunity to follow up his discovery, which he made during a one-month summer vacation. He was not able to publish his work until a year later, and in the meantime Faraday had made a similar discovery and published his results.

Faraday is known as the discoverer of "electromagnetic induction" (production of a current by magnetism) not simply because he established official priority by first publication, but primarily because he conducted exhaustive investigations into all aspects of the subject. His earlier experiments and his thinking about lines of force had suggested the possibility that a current in one wire ought to be able to induce a





Faraday's laboratory at the Royal Institution.

Michael Faraday (1791-1867) was the son of an English blacksmith. In his own words,

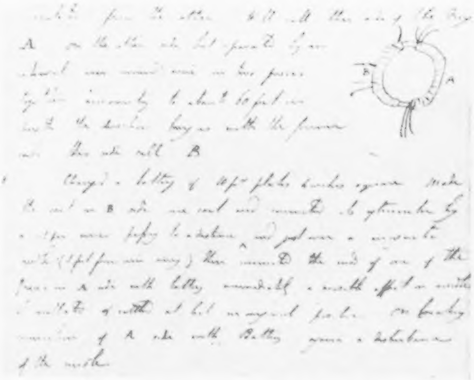
> My education was of the most ordinary description consisting of little more than the rudiments of reading, writing and arithmetic at a common day school. My hours out of school were passed at home and in the streets

At the age of twelve he went to work as an errand boy at a bookseller's store. Later he became a bookbinder's assistant. When Faraday was about nineteen he was given a ticket to attend a series of lectures given by Sir Humphrey Davy at the Royal Institution in London. The Royal Institution was an important center of research and education in science, and Davy was Superintendent of the Institution. Faraday became strongly interested in science and undertook the study of chemistry by himself. In 1813, he applied to Davy for a job at the Royal Institution and Davy hired him as a research assistant. Faraday soon showed his genius as an experimenter. He made important contributions to chemistry, magnetism, electricity and light, and eventually succeeded Davy as superintendent of the Royal Institution. Because of his many discoveries, Faraday is generally regarded as one of the greatest of all experimental scientists. Faraday was also a fine lecturer and had an extraordinary gift for explaining the results of scientific research to nonscientists. His lectures to audiences of young people are still delightful to read. Two of them, "On the Various Forces of Nature" and "The Chemical History of a Candle," have been republished in paperback editions. Faraday was a modest, gentle and deeply religious man. Although he received many international scientific honors he had no wish to be knighted, preferring to remain without the title of "Sir."

current in a nearby wire. The induction might take place directly between small sections of current, as a consequence of the force studied by Ampère (Sec. 14.8). Or it might be that the magnetic lines of force in the space around the first current could produce a current in the other wire.

How does electromagnetic induction take place? Oersted and Ampère had shown that a steady electric current produced a steady magnetic effect around the circuit carrying the current. One might think that a steady electric current could somehow be generated if a wire were placed near or around a magnet, although a very strong magnet might be needed. Or a steady current might be produced in one circuit if a very large current flows in another circuit nearby. Faraday tried all these possibilities, with no success.

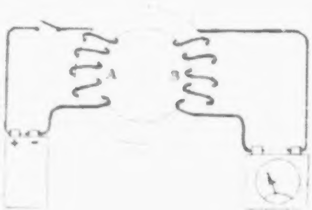
Finally, in 1831, Faraday found the solution. He discovered that a current appeared in one wire only when the current in the other wire started or stopped! When a current started to flow in one wire, a current was indeed induced in the second wire, but it lasted only for a moment. As long as there was a steady current in the first wire, there was no current in the second wire; but when the current in the first wire was stopped, again there was a momentary current induced in the second wire.



The page in Faraday's diary where he recorded the first successful experiment in electromagnetic induction, August 29, 1831. (About 1/3 actual size)

To summarize Faraday's result: a current can induce another current only by changing. A steady current in one wire cannot induce a current in another wire.

Faraday was not satisfied with merely observing and reporting this result. Guided by his concept of "lines of force," he tried to find out what were the essential factors involved in electromagnetic induction, as distinguished from the accidental circumstances of his first experiment.

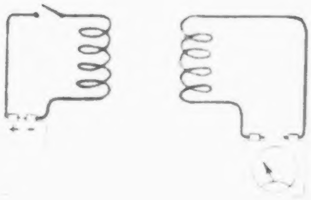


According to Faraday's theory, the changing current in the primary coil (A) would change the lines of magnetic force in the iron ring, and the change in magnetic lines of force in the part of the ring near the secondary coil (B) would induce a current in the secondary coil. But if this was really the correct explanation of induction, Faraday asked himself, shouldn't it be possible to produce the same effect in another way? In particular:

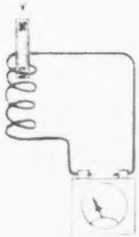
(1) is the iron ring really necessary to produce the induction effect, or does it merely intensify an effect that would occur anyway whenever magnetic lines of force are present in space?

(2) is the primary coil really necessary, or could current

be induced merely by changing magnetic lines of force in some other way, such as by moving a magnet relative to the wire?



Faraday answered these questions almost immediately by further experiments. First, he showed that the iron ring was not necessary; starting a current in one coil of wire would induce a momentary current in a nearby coil. Second, he found that when a bar magnet was inserted into the end of a coil of wire, a current was induced at the instant of insertion. In Faraday's words,



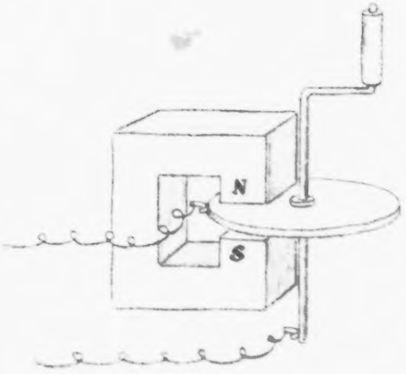
> A cylindrical bar magnet...had one end just inserted into the end of the helix cylinder; then it was quickly thrust in the whole length and the galvanometer needle moved; then pulled out and again the needle moved, but in the opposite direction. The effect was repeated every time the magnet was put in or out....

Having done these and many other experiments, Faraday stated his general principle of electromagnetic induction: changing lines of magnetic force can cause a current in a wire. The "change" in lines of force can be produced either by (a) a magnet moving relative to a wire or (b) a changing current. (Faraday found it convenient to speak of wires "cutting across" lines of force.) He later used the word *field* to refer to the arrangement and intensity of lines of force in space. We can say, then, that a current is induced in a circuit by variations in the magnetic field around the circuit. Such a variation may be caused either by relative motion of wire and field or just by the change in intensity of the field.

SG 15.3

SG 15.4

So far Faraday had been able to produce only momentary surges of current by induction. Is it possible to produce a steady current by electromagnetic induction? To do this one has to create a situation in which magnetic lines of force are *always changing* relative to the conductor. (The relative change can be produced either by moving the magnet or by moving the conductor.) This is just what Faraday did: he turned a copper disc between the poles of a magnet. A steady current was produced in a circuit connected to the disc through brass brushes. This device, called the "Faraday disc dynamo," was the first electric current generator. Although this particular arrangement did not turn out to be very practical, at least it showed that continuous generation of electricity was possible.



The production of a continuous current was important not only for the understanding of the connection between electricity and magnetism; it also brought with it the possibility of producing electricity on a large scale. The production of electricity involves changing energy from one form to another. In the voltaic cell (Chapter 14) chemical energy—the energy of formation of chemical compounds—is converted into electrical energy. But it is not practical to produce large amounts of electrical energy by this means, although voltaic cells are useful for many portable applications; automobiles and flashlights for example. Since there is a vast supply of mechanical energy available to produce electrical energy on a large scale, some means of converting mechanical energy into electrical energy is needed. This mechanical energy may be in the form of the potential energy of water at high elevation; or it may be in the form of continuous mechanical motion produced, for example, by a steam engine. The discovery of electromagnetic induction showed that it was feasible to produce electricity by mechanical means. In this sense Faraday can rightly be regarded as the father of the modern electrical age.

Although Faraday realized the practical importance of his discoveries, his primary interest was always in pure science. He left the development of the generator and the motor to others. On the other hand, the inventors and engineers who were interested in the practical and profitable applications of electricity did not know much about physics, and most of the progress during the next fifty years was made by trial and error. In following the development of modern electrical technology, we will see several problems that could have been solved much earlier if a physicist with Faraday's knowledge had been working on them.

Q3 What did Henry and Faraday discover independently but at almost the same time?

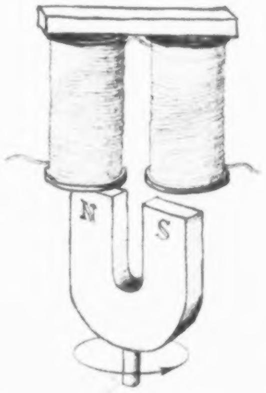
Q4 What in general is meant by "electromagnetic induction?"

Q5 What did Faraday find necessary for one current to induce another?

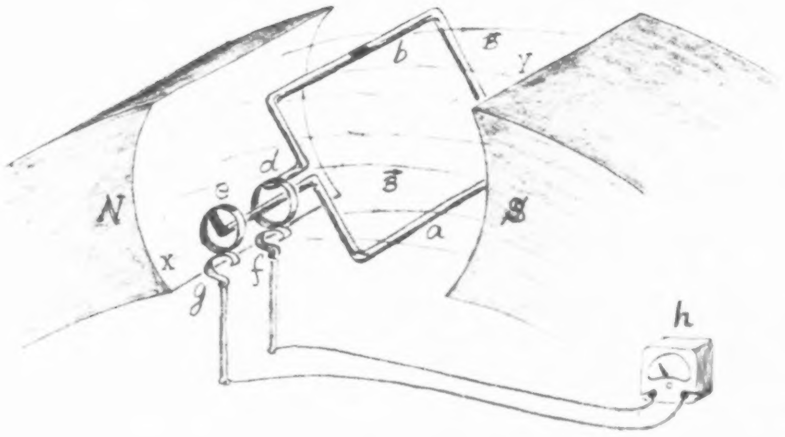
Q6 What was the first electric current generator?

15.5 Generating electricity from magnetism: the dynamo.

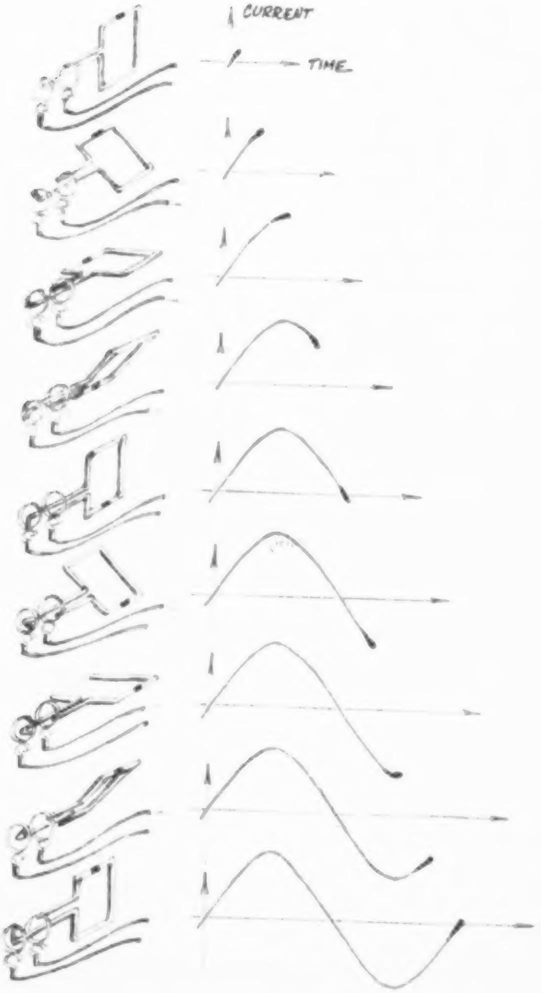
Faraday had shown that when a conducting wire moves through a magnetic field, a current is produced. Whether it is the wire or the magnetic field that moves doesn't matter; what counts is the relative motion. Once the principle of electromagnetic induction had been discovered, the path was open to try all kinds of combinations of wires and moving magnets, magnets and moving wires, and so forth. We shall pass over the details of most of these technical developments and simply describe one basic type of generator (or "dynamo") which was frequently used in the nineteenth century.



One generator of 1832 had a permanent horseshoe magnet rotated by hand beneath two stationary coils.



This form of generator is basically a coil of wire rotated in a magnetic field. The rotating coil is connected to an external circuit by sliding contacts. In the diagram on the left a rectangular loop of wire, with long sides a and b, is rotated around an axis XY between the north and south poles of a magnet. Two conducting rings d and e are connected to the loop, and also rotate around the axis; conducting brushes f and g are provided to complete a circuit through a meter at h that indicates the current produced. The complete circuit is abdfhgea. (Note that the wire goes from a through ring d without touching it and connects to e.)

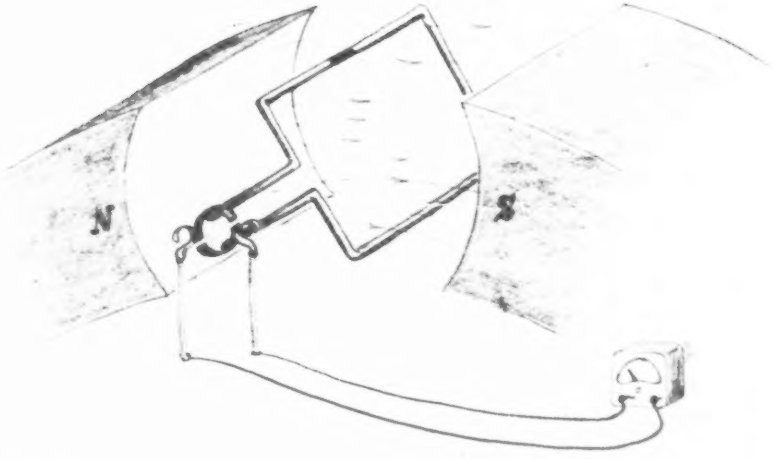


Initially the loop is at rest, and no charge flows through it. Now suppose we start to rotate the loop. The wire will have a component of its motion perpendicular to the direction of the magnetic lines of force; that is, the wire "cuts" through lines of force. This means that an electric current will be induced in the loop. This induction is just the experimental fact discovered by Faraday and Henry.

Because the charges in the part of the loop labeled b are being moved across the magnetic field, they experience a magnetic force given by qvB (see Sec. 14.13). The charges in the wire will be pushed "off to the side" by the magnetic field that is moving past them; "off to the side" this time is along the wire.

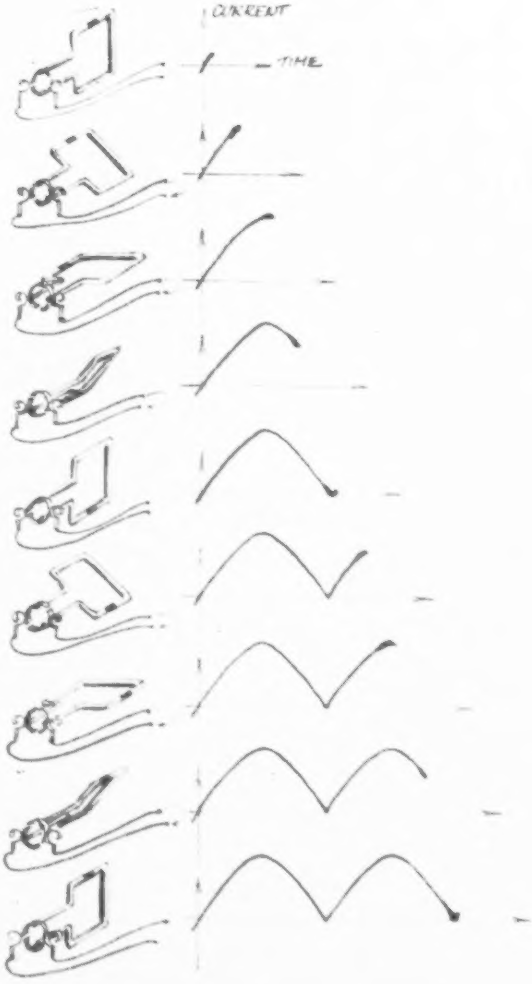
What about a? That side of the loop is also moving through the field and "cutting" lines of force, but in the opposite direction. So the charges in a are pushed in the opposite direction along the wire to those in b. This is just what is needed; the two effects reinforce each other in generating a current around the loop.

The generator we have just described produces what is called alternating current, because the current periodically reverses its direction. At the time this kind of generator was first developed, in the 1830's, alternating current could not be used to run machines. Instead, direct current was desired.



In 1832, Ampère announced that his instrument-maker, Hippolyte Pixii, had solved the problem of generating direct current. Pixii invented a device called the commutator (the word means to interchange, or to go back and forth). The commutator is a split cylinder inserted in the circuit so that the brushes f and g, instead of always being connected to the same part of the loop, reverse connections each time the loop passes through the vertical position. Just as the direction of current induced in the loop reverses, the contacts reverse: as a result, the current in the outside circuit is always in the same direction.

Although the current from Pixii's generator is always in the same direction, it is not constant but fluctuates rapidly between zero and its maximum value. This fluctuating current produces fluctuating magnetic fields which prevent the smooth operation of the generator and waste energy. The generator can be greatly improved by adding many loops and commutators in such a way that their induced currents have maximum and zero values at different times; the total current is then more uniform.

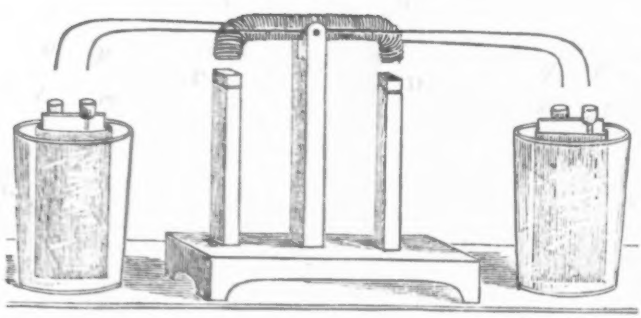


Q7 **What is the position of the rotating loop for maximum current? minimum?**

Q8 **What is the purpose of the commutator?**

15.6 The electric motor. An electric motor is basically just a generator run "backwards." For example, if the meter h in the circuit sketched at the top of page 84 were replaced by a battery, current would be driven around the circuit. The current in the coil would interact with the magnetic field of the magnet, and the coil would be forced to rotate.

Motors could have been made before generators, and in fact they were. In 1821, Michael Faraday exhibited his electromagnetic rotator (described in Sec. 15.3) at the Royal Institution in London. Other electric motors were designed by various scientists in Europe and America. One of them was Joseph Henry's "rocking electromagnet." Henry wrote as follows about his motor:



Henry's electromagnetic motor (1831)

> I have lately succeeded in producing motion in a little machine by a power, which, I believe, has never before been applied in mechanics—by magnetic attraction and repulsion.
>
> Not much importance, however, is attached to the invention, since the article in its present state can only be considered a philosophical toy; although in the progress of discovery and invention, it is not impossible that the same principle, or some modification of it on a more extended scale, may hereafter be applied to some useful purpose.

The reason for Henry's failure to be very enthusiastic about the importance of his invention is that as long as electric current was only available from batteries, electric motors could not compete with steam engines. The economics of the situation was summarized in a leading British scientific journal as follows:

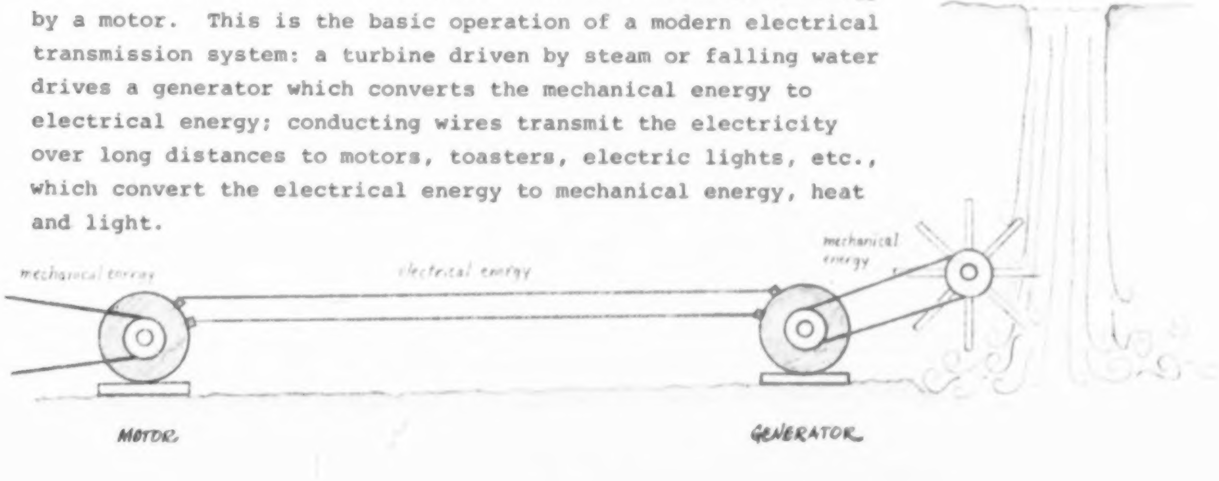
> [Notwithstanding] the numerous attempts which have been made to apply electro-magnetism as a power for moving machines...and the large amount of money which has been expended in the construction of machines, the public are not in possession of any electro-magnetic machine which is capable of exerting any power economically.... Estimations made by Messrs. Scoresby and Joule, and the results obtained by Oersted, ...very nearly agree; and it was stated that one gr. of coal consumed in the furnace of a Cornish [steam] engine lifted 143 lbs. 1 foot high, whereas one gr. of zinc consumed in a battery lifted only 80 lbs. The cost of [one hundred weight] of coal is under 9 pence, and cost of [one hundred weight] of zinc is above 216 pence. Therefore under the most perfect conditions, magnetic power must be nearly 25 times more expensive than steam power.... the attention of engineers and experimentalists should be turned at present, not to contriving of perfect machines for applying electro-magnetic power but to the discovery of the most effectual means of disengaging the power itself from the conditions in which it existed stored up in nature. (Philosophical Magazine, 1850)

The dynamo, invented by Faraday and Henry in 1832, was no more economical at first than the battery. It was only another "philosophical toy." Electric generators that could produce power cheaply enough to be commercially successful were not developed until nearly 50 years later. The intervening period was one of numerous inventions that aroused great temporary enthusiasm and ambitious plans, followed by disillusion resulting from unanticipated practical difficulties. But the hope of a fortune to be made by providing cheap power to the world spurred on each new generation of inventors, and knowledge about the physics and technology of electromagnetic systems gradually accumulated.

It is convenient though rarely accurate to ascribe the beginnings of an era to one man, in one place, performing one act, at one time. In reality, with many men thinking about and experimenting in a particular scientific field, the situation becomes favorable for a breakthrough, and only a seemingly trivial chance event may be needed to get things going.

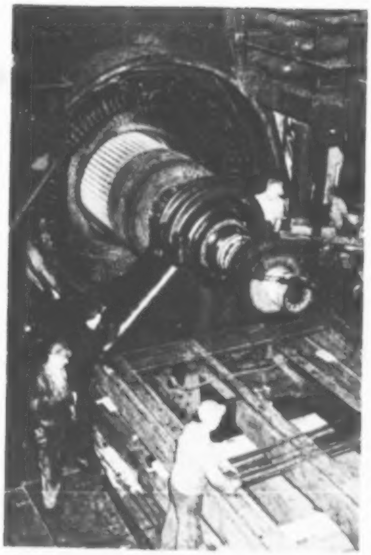
The chance event that marks the beginning of the electric power age was an accidental discovery at the Vienna Exhibition of 1873. As the story goes, it was an unknown workman at the Exhibition who just happened to hook up the two dynamos that had been designed by a Belgian inventor, Zenobe Gramme. One dynamo ran as an electric motor on electricity generated by the other.

This accidental discovery, that a generator could be run "backwards" to serve as a motor, was immediately utilized at the Exhibition in a spectacular public demonstration: the electric motor was made to drive a pump that supplied water for a small waterfall. Thus electromagnetic induction was first used to convert mechanical energy into electrical energy by means of a generator, which could be transmitted over a considerable distance and converted back into mechanical energy by a motor. This is the basic operation of a modern electrical transmission system: a turbine driven by steam or falling water drives a generator which converts the mechanical energy to electrical energy; conducting wires transmit the electricity over long distances to motors, toasters, electric lights, etc., which convert the electrical energy to mechanical energy, heat and light.



15.6

The development of electrical generators shows the interaction of science and technology in a different light than did the development of steam engines. As was pointed out in Chapter 10, the early steam engines were developed by practical inventors who had no knowledge of what we now consider to be the correct theory of heat (thermodynamics). In fact, it was the development of the steam engine itself, and attempts by Sadi Carnot and others to improve its efficiency by theoretical analysis, that was one of the major historical factors leading to the establishment of thermodynamics. In that case, the technology came before the science. But in the case of electromagnetism, a large amount of scientific knowledge was built up by Ampère, Faraday, Kelvin and Maxwell before there was any serious attempt at practical application. The scientists who understood electricity better than anyone else were not especially interested in commercial applications, and the inventors who hoped to make huge profits from electricity knew very little of the theory. Although after Faraday announced his discovery of electromagnetic induction people started making generators to produce electricity immediately, it was not until 40 years later that inventors and engineers started to become familiar with the concepts of lines of force and field vectors. With the introduction of the telegraph, telephone, radio and alternating-current power systems, the amount of mathematical knowledge needed to work with electricity became quite large, and universities and technical schools started to give courses in electrical engineering. In this way there developed a group of specialists who were familiar with the physics of electricity and also knew how to apply it.



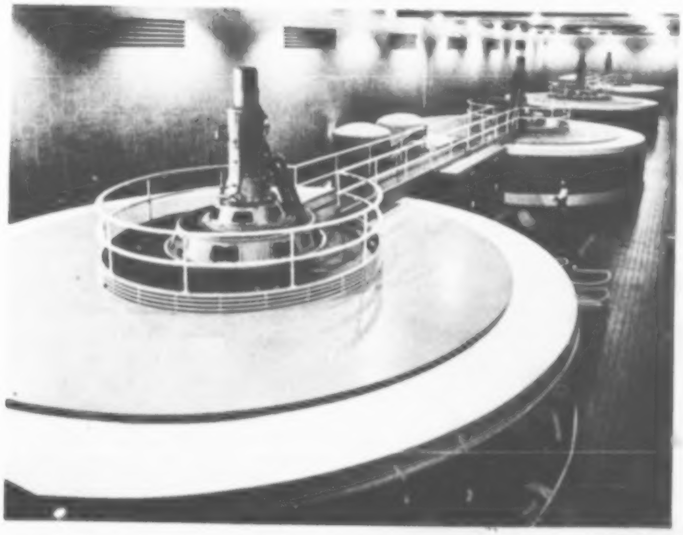
Insides of a commercial generator. As in almost all large generators, the coils of wire are around the outside and electromagnets are rotated inside.

The growth of the electrical industry has been largely due to the public demand for electrical products. One of the first of these to be commercially successful in the United States was the electric light bulb.

Q9 How would you make an electric motor out of a generator?

Q10 What prevented the electric motor from being an immediate economic success?

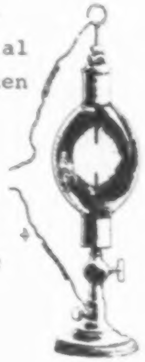
Q11 What chance event led to the beginning of the electric power age?



Water-driven electric generators producing power at the Tennessee Valley Authority. The plant can generate electric energy at a rate of over 100,000,000 watts.

15.7 The electric light bulb. At the beginning of the nineteenth century, illumination for buildings and homes was provided by candles and oil lamps. Street lighting in cities was practically nonexistent, in spite of sporadic attempts in London and New York to require householders to hang lights outside their houses at night. The natural gas industry was just starting to change this situation, and the first street lighting system for London was provided in 1813 when gas lights were installed on Westminster Bridge. The introduction of gas lighting in factories was not entirely beneficial in its social effects, since it enabled employers to lengthen an already long and difficult working day.

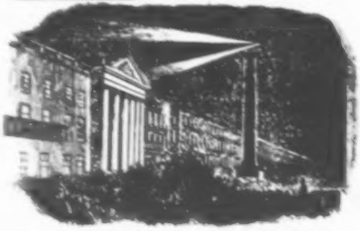
In 1801, the British chemist Humphry Davy noted that a brilliant spark appeared when he broke contact between two carbon rods which were connected to the two terminals of a battery. This discovery led to the development of the "arc light."



Davy's arc lamp

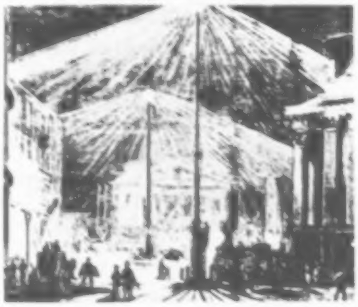
The arc light was not practical for general use until steam-driven electric generators had replaced expensive batteries as a source of electric current. In the 1860's and 1870's, arc lights began to be used for street lighting and lighthouses. However, the arc light was too glaring and too expensive for use in the home. The carbon rods burned up in a few hours because of the high temperatures produced by the arc, and the need for frequent service and replacement made this system inconvenient.

Demonstrations of the new electric light during a visit of Queen Victoria and Prince Albert to Dublin, Ireland. From Illustrated London News, August 11, 1849.

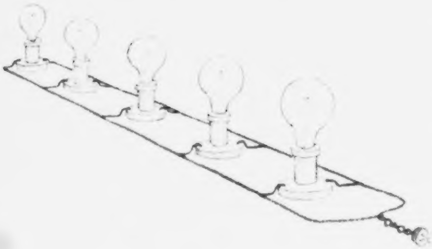


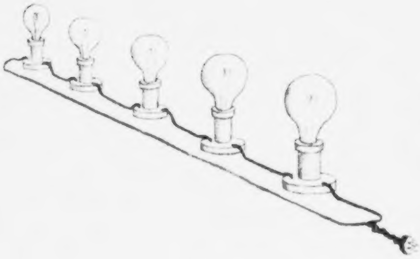
As Humphry Davy and other scientists showed, light can be produced simply by producing a current in a small wire (often called a "filament") to heat it to a high temperature. This is known as incandescent lighting. The major technical drawback was that the material of the filament gradually burned up. The obvious solution was to enclose the filament in a glass container from which all the air had been removed. But this was easier said than done. The vacuum pumps available in the early nineteenth century could not produce a sufficiently good vacuum for this purpose. It was not until 1865, when Hermann Sprengel in Germany invented an exceptionally good vacuum pump, that the electric light bulb in its modern form could be developed. (The use of Sprengel's pump in scientific experiments by Crookes and others was also vital to the discoveries in atomic physics which we will discuss in Chapter 18.)

In the late 1800's, dynamo powered arc-lamps were used in some European cities.



Thomas A. Edison (1847-1931) was not the first to invent an incandescent light using the Sprengel pump, nor did he discover any essentially new scientific principles. What he





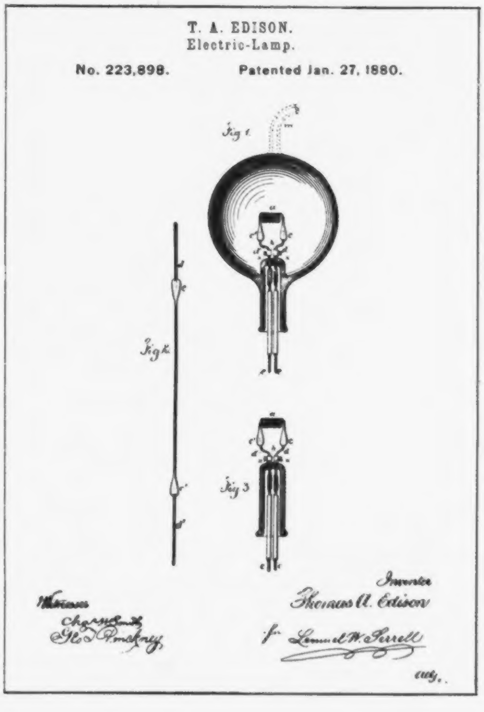
See the article "The Invention of the Electric Light" in Project Physics Reader 4.

did was develop a practical light bulb which could be used in homes, and (even more important) a distribution system for electricity. His system not only made the light bulb practical but also opened the way for mass consumption of electrical energy in the United States.

Edison started from the basic assumption that each customer must be able to turn on and off his own light bulbs without affecting the other lights on the line. This meant that the lights must be connected "in parallel"—like the rungs of a ladder—rather than "in series."

The choice of parallel rather than series circuits—a choice based on the way Edison thought the consumer would want to use the system—had important technical consequences. In a series circuit the same current would go through each light. In a parallel circuit only part of the total current goes through each light. To keep the total current from being too large, the current in each bulb would have to be rather small.

As we pointed out in Chapter 14, the heating effect of a current depends on both the resistance of the wire and the amount of current it carries. The rate at which heat energy is produced is proportional to I^2R; that is, it goes up directly as the resistance, but increases as the square of the current. Therefore most inventors used high-current low-resistance bulbs, and assumed that parallel circuits would not be practical. But Edison realized that a small current will have a large heating effect if the resistance is high enough.

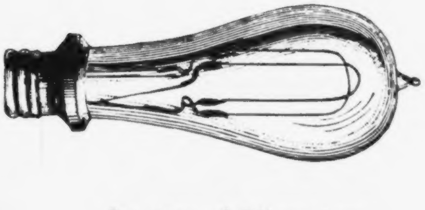


T. A. EDISON.
Electric-Lamp.

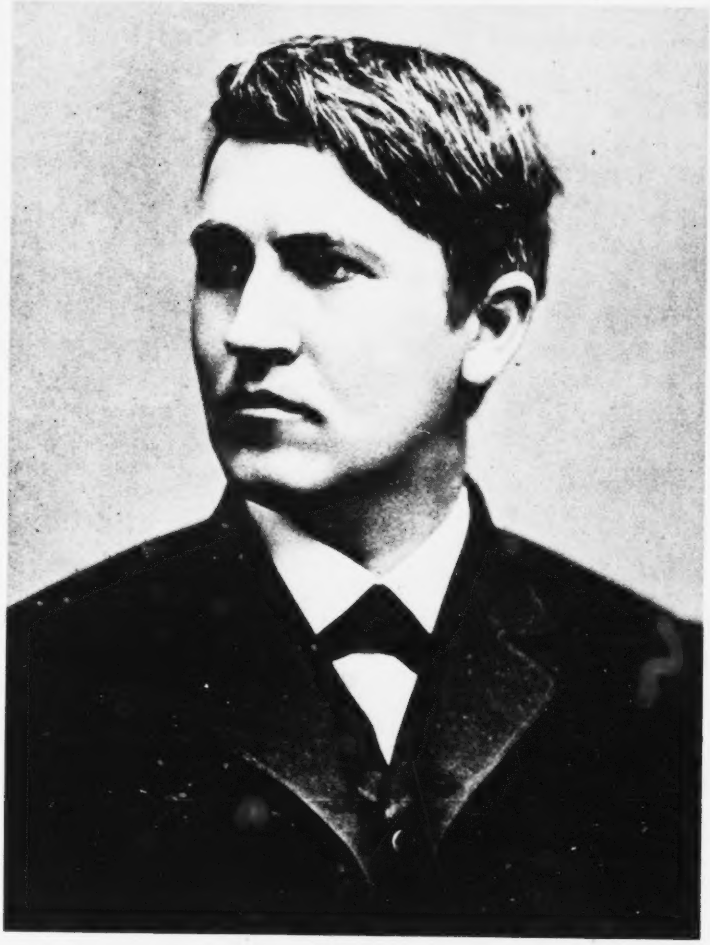
No. 223,898. Patented Jan. 27, 1880.

Witnesses
Chas. H. Smith
Geo. T. Pinckney

Inventor
Thomas A. Edison
per Lemuel W. Serrell
atty.



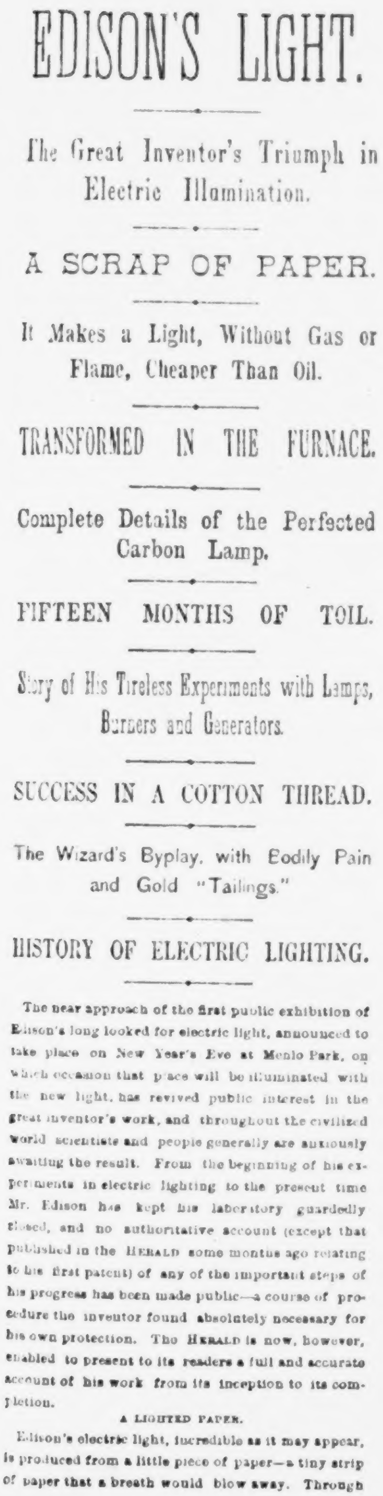
One type of Edison lamp. Note the familiar filament and screw-type base.



Edison was born at Milan, Ohio, and spent most of his boyhood at Port Huron, Michigan. His first love was chemistry, and to earn money for his chemical experiments, he set up his own business enterprises. He ran two stores in Port Huron, one for periodicals and the other for vegetables; hired a newsboy to sell papers on the Grand Trunk Railway running between Port Huron and Detroit; published a weekly newspaper; and ran a chemical laboratory in the baggage car of the train. His financial empire was thus growing rapidly when, in 1862 (he was now fifteen), a stick of phosphorus in his laboratory caught fire and destroyed part of the baggage car. As a result, his laboratory and newspaper equipment were evicted from the train, and he had to look around for another base of operations.

It was not long before his bad luck with the phosphorus fire was offset by a piece of good luck: he was able to save the life of the son of the station agent by pulling him out of the path of an oncoming train. In gratitude, the station agent taught Edison the art of telegraphy, and thus began Edison's career in electricity.

At left are shown two portraits of Edison. On the opposite page is a copy of the drawing that accompanied his patent on the incandescent lamp.



EDISON'S LIGHT.

The Great Inventor's Triumph in Electric Illumination.

A SCRAP OF PAPER.

It Makes a Light, Without Gas or Flame, Cheaper Than Oil.

TRANSFORMED IN THE FURNACE.

Complete Details of the Perfected Carbon Lamp.

FIFTEEN MONTHS OF TOIL.

Story of His Tireless Experiments with Lamps, Burners and Generators.

SUCCESS IN A COTTON THREAD.

The Wizard's Byplay, with Bodily Pain and Gold "Tailings."

HISTORY OF ELECTRIC LIGHTING.

The near approach of the first public exhibition of Edison's long looked for electric light, announced to take place on New Year's Eve at Menlo Park, on which occasion that place will be illuminated with the new light, has revived public interest in the great inventor's work, and throughout the civilized world scientists and people generally are anxiously awaiting the result. From the beginning of his experiments in electric lighting to the present time Mr. Edison has kept his laboratory guardedly closed, and no authoritative account (except that published in the HERALD some months ago relating to his first patent) of any of the important steps of his progress has been made public—a course of procedure the inventor found absolutely necessary for his own protection. The HERALD is now, however, enabled to present to its readers a full and accurate account of his work from its inception to its completion.

A LIGHTED PAPER.

Edison's electric light, incredible as it may appear, is produced from a little piece of paper—a tiny strip of paper that a breath would blow away. Through

First newspaper account of Edison's invention (New York Herald, December 21, 1879)

15.7

So Edison started to search for a suitable high-resistance substance for his filaments. To make such a filament, he first had to bake or "carbonize" a thin piece of a substance; then he would seal it inside an evacuated glass bulb with wires leading out. His assistants tried more than 1,600 kinds of material: "paper and cloth, thread, fishline, fiber, celluloid, boxwood, coconut-shells, spruce, hickory, hay, maple shavings, rosewood, punk, cork, flax, bamboo, and the hair out of a redheaded Scotchman's beard." His first high-resistance lamp was made with carbonized cotton thread, enclosed in a high-vacuum sealed bulb. It burned continuously for two days before it fell apart. This was in October 1879. The following year, Edison produced lamps with filaments made of Bristol board and bamboo.

The Edison Electric Light Company began to install lighting systems in 1882. After only three years of operation, the Edison company had sold 200,000 lamps. It had a virtual monopoly of the field, and began to pay handsome dividends to its stockholders.

The electric light bulb has undergone some modification since Edison's original invention. For example, the carbonized filaments of the older lamps have been replaced in newer bulbs by tungsten, which has the advantages of greater efficiency and longer life.

The widespread use of light bulbs (confirming the soundness of Edison's theory about what people would buy) led to the rapid development of systems of power generation and distribution. The need for more power for lighting led to the invention of better generators, the replacement of direct current transmission by alternating current (see below), the harnessing of waterfalls, and the invention of the steam turbine. Then, success in providing larger quantities of energy at lower cost made other uses of electricity practical. Once homes were wired for electric lights, the current could be used to run sewing machines, vacuum cleaners, washing machines, toasters, and (later on) refrigerators, freezers, radios and television sets.

We have now become so accustomed to the more sophisticated and spectacular applications of electricity that it is hard to realize the impact of something as simple as the electric light bulb. But most people who lived through the period of electrification—for example, in the 1930's and 1940's in many rural areas of the United States—agreed that the one single electrical appliance that made the greatest difference in their own lives was the electric light bulb.

Q12 Why weren't arc lights used for illuminating homes?

Q13 What device was essential to the development of the incandescent lamp?

Q14 Why did Edison require a substance with a high resistance for his light bulb filaments?

15.8 Ac versus dc and the Niagara Falls power plant. In Sec. 15.5 we stated that the usual form of electrical generator produces alternating current, which is changed into direct current by the use of a commutator. The reason for converting ac into dc was the general belief, held throughout most of the nineteenth century, that only dc was useful in the applications of electricity. However, as the demand for electrical power increased, some of the inherent disadvantages of dc became evident. One disadvantage was the fact that having a commutator complicated the design of the generator, especially if the ring had to be rotated at high speed. This difficulty was even more serious after the introduction of steam turbines in the 1890's, since turbines work most efficiently when run at high speeds. Another disadvantage was the fact that there was no convenient way to change the voltage of direct current.

The use of high voltages to minimize power loss. One reason for wanting to change the voltage which drives the current in a transmission system involves the amount of power lost in heating the transmission wires. When there is a current I in a transmission wire of resistance R, the amount of power expended as heat is proportional to the resistance and to the square of the current:

$$\text{power loss} = I^2R.$$

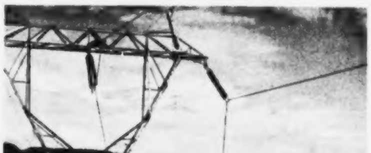
This means that for transmission lines of a given resistance R, one wants to make the current I as small as possible in order to minimize the power loss in transmission. On the other hand, the amount of power that can be transmitted depends on the voltage as well as on the amount of current:

SG 15.12

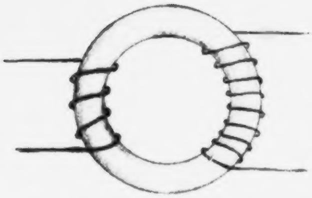
$$\text{power} = IV.$$

In order to balance the effect of making I small (in order to cut down power loss by heating of the wire) V must be made large. In other words, economic factors require that electricity should be transmitted at high voltages.

On the other hand, for most of the applications of electricity, especially in homes, it is neither convenient nor safe to use high voltages. Also, most generators cannot produce electricity at very high voltages (which would re-



quire excessively high speeds of the moving parts). Therefore we need some way of "stepping up" the electricity to a high voltage for transmission, and some way of "stepping it down" again for use at the other end. In short, we need a transformer.



A transformer can easily be made by a simple modification of Faraday's induction coil (Sec. 15.4). Faraday was able to induce a current in a coil of wire (which we call the secondary coil) by winding this coil around one side of an iron ring, and then changing a current in another coil (the primary coil) which is wound around the other side of the ring. A current is induced in the secondary coil when the primary current changes. If the primary current is changing all the time, then a current will continually be induced in the secondary. An alternating current in the primary coil (as from a generator without a commutator) will induce an alternating current in the secondary coil.

We need just one additional fact to make a useful electric transformer: if the secondary coil has fewer turns than the primary, the alternating voltage produced across the secondary coil will be lower than the voltage across the primary; if the secondary has more turns than the primary, the voltage produced across the secondary will be greater than across the primary. This fact was discovered by Joseph Henry, who built the first transformer in 1838.

Electricity could be generated on a large scale most economically with a high-speed steam turbine, but this is difficult to do if we have to use a commutator to convert ac in the coils inside the generator into dc in the outside circuit. (The commutator is likely to fall apart under the huge strains set up by high-speed rotation.) Furthermore, it is desirable to use very high voltages (and low currents) on long-distance transmission lines to minimize power loss by heating; but the only practical device for changing voltage is the transformer, which works only for ac, not for dc. Commutators could be eliminated and voltages changed easily if ac were used for large-scale generation and distribution of electric power.

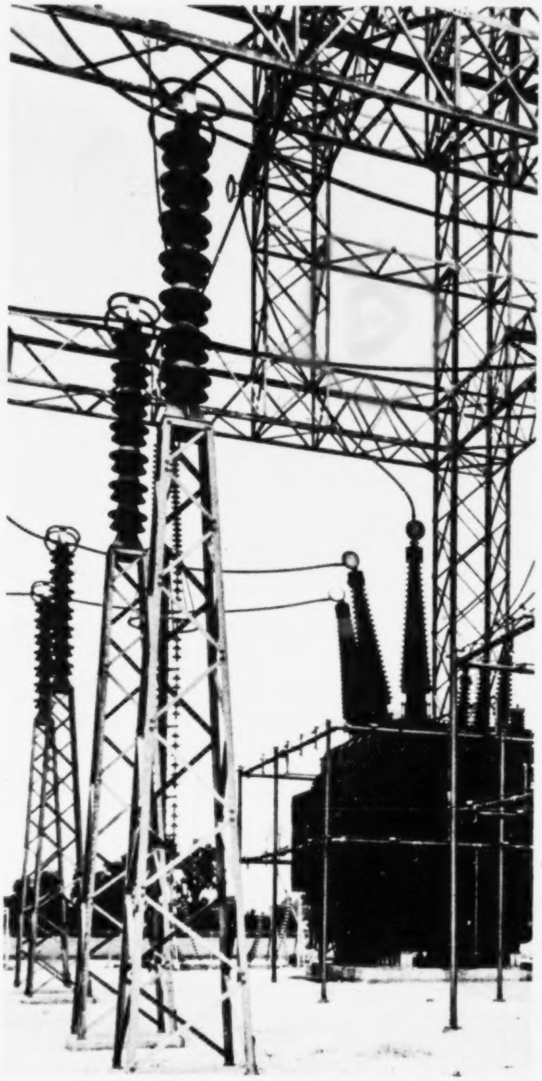
The first ac system was demonstrated by Gaulard and Gibbs of Paris in 1883. An experimental line which powered arc and incandescent lighting, through transformers, was installed in a railway line in London in 1884, and another one shortly afterward in Italy. An American engineer, George Westinghouse, saw the Gaulard-Gibbs system exhibited in Italy and purchased the American patent rights for it. Westinghouse had already gained a reputation by his invention of the railway air brake, and had set up a small electrical engineering company in Pittsburgh in 1884. After making some improvements in the transformers, the Westinghouse Electric Company set up its first commercial installation to distribute alternating current for incandescent lighting in Buffalo, New York, in 1886.

At the time of the introduction of the Westinghouse ac system in the United States, the Edison Electric Light Company held almost a complete monopoly of the incandescent lighting business. The Edison Company had invested large amounts of money in providing dc generating plants and distribution systems for most of the large cities. Naturally Edison was alarmed by a new company which claimed to produce the same kind of illumination with a much cheaper system. There was a bitter public controversy, in which Edison attempted to show that ac is unsafe because of the high voltages used for transmission. In the middle of the dispute, the New York State Legislature passed a law establishing electrocution as a means of capital punishment, and this seems to have aroused some of the popular fear of high voltage.

Nevertheless, the Westinghouse system continued to grow, and since there were no spectacular accidents, the public accepted ac as being reasonably safe. The invention of the "rotary converter" made it possible to convert ac into dc for use in local systems already set up with dc equipment, or to power individual dc motors. Consequently the Edison company (later merged into General Electric) did not have to go out of business when ac was generally adopted.

The final victory of the ac system was assured in 1893, when the decision was made to use ac for the new hydroelectric plant at Niagara Falls. In 1887, businessmen in Buffalo had pledged $100,000 to be offered as a prize "to the inventors of the World" who would design a system for utilizing the power of the Niagara River "at or near Buffalo, so that such power may be made practically available for various purposes throughout the city." The contest attracted worldwide attention, not only because of the large prize but also because large quantities of electrical power had never before been transmitted over such a distance—it was 20 miles from Niagara Falls to Buffalo. The success or failure of this venture would influence the future development of electrical distribution systems for other large cities.

It was a close decision whether to use ac or dc for the Niagara Falls system. The demand for electricity in 1890



Commercial Distribution of Electric Power

The commercial distribution of ac electric power requires elaborate transmission facilities. Generator output voltages of about 10^4 volts are stepped up to about 10^5 volts for transmission, stepped down to about 10^4 volts for local distribution, and further stepped down to about 10^2 volts by neighborhood power-pole transformers. Within the home, it may be stepped down further (often to 6 volts for doorbells and electric trains) and stepped up by transformers in radio and TV sets for operating high-voltage tubes.

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5000
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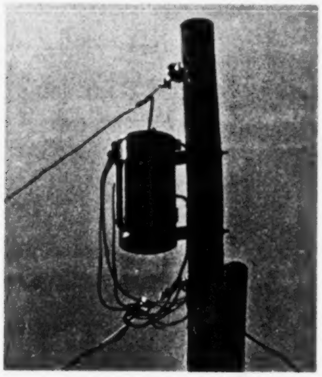
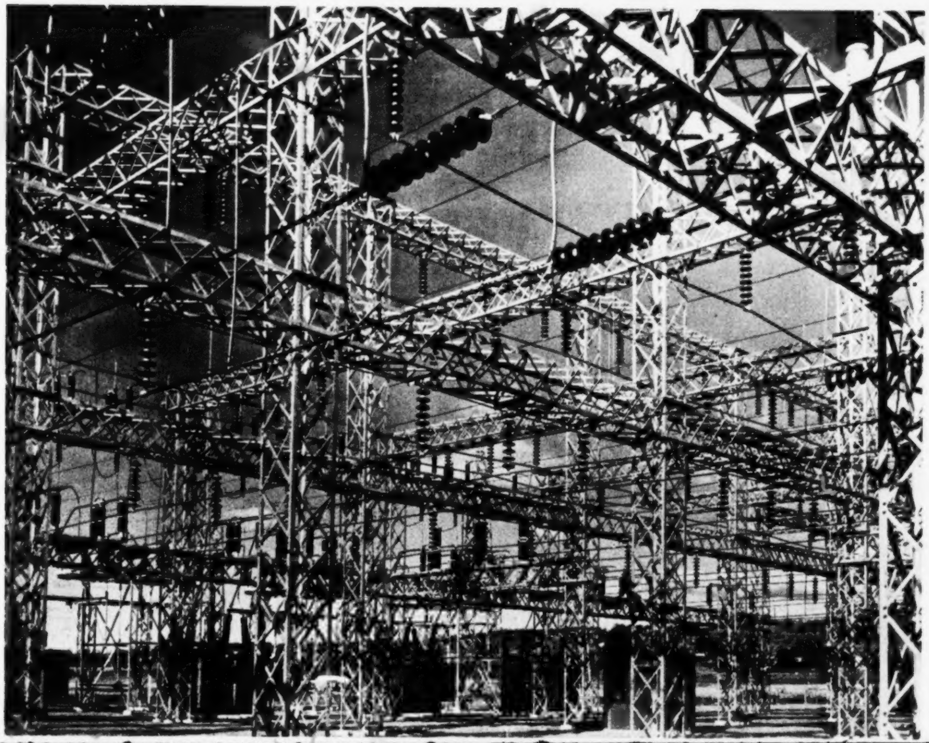
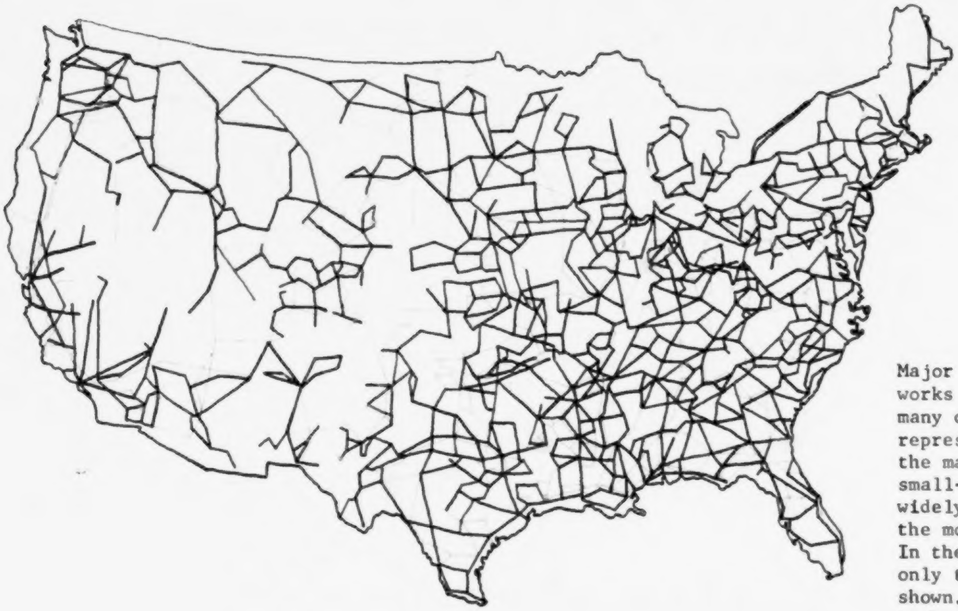
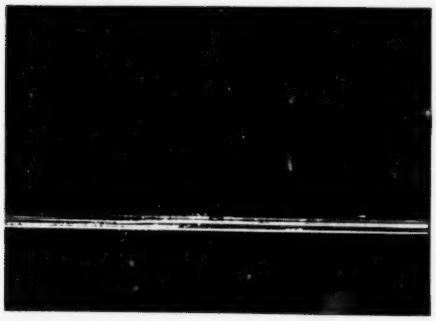






Major electric transmission networks in the United States. In many cases several lines are represented by a single line on the map. Not shown are the small-capacity lines serving widely scattered populations in the mountainous and desert areas. In the densely-populated areas only the high-voltage lines are shown. Lines drawn in gray are to be completed by 1970.

The interdependence of our modern electrical civilization was dramatically demonstrated at about 5 p.m. on November 9, 1965, when a faulty electrical relay in Canada caused a power failure and total blackout throughout most of the northeastern part of the United States.



was mainly for lighting, which meant that there would be a peak demand in the evening; the system would have to operate at less than full capacity during the day and late at night. Some engineers proposed that, even though ac could be generated and transmitted more efficiently, a dc system would be cheaper to operate if there were much variation in the demand for electricity. This was because batteries could be used to back up the generators in periods of peak demand. Thomas Edison was consulted, and without hesitation he recommended dc. But the Cataract Construction Company, which had been formed to administer the project, delayed making a decision.

The issue was still in doubt in 1891 when, at the International Electrical Exhibition in Frankfort, Germany, an ac line carrying sizable quantities of power from Frankfort to Lauffen (a distance of 110 miles) was demonstrated. Tests of the line showed an efficiency of transmission of 77%. That is, for every 100 watts fed in at one end of the line, only 23 were wasted by heating effects in the line, and the other 77 were delivered as useful power. The success of this demonstration reinforced the gradual change in expert opinion in favor of ac over dc, and the Cataract Company finally decided to construct an ac system.

After the ac system had been established, it turned out that the critics had been wrong in their prediction about the variation of demand for electricity throughout the day. Electricity was to have many uses besides lighting. In the 1890's, electric motors were already being used for street railway cars, sewing machines and elevators. Because of these diverse uses, the demand for electricity was spread out more evenly during each 24-hour period. In the particular case of the Niagara Falls power plant, the source of energy—the flow of water down the Niagara River—made it possible to produce energy continuously without much extra cost. (The boiler for a steam turbine would either have to be kept supplied with fuel during the night, or shut down and started up again in the morning.) Since hydroelectric power was available at night at low cost, new uses for it became possible. The Niagara Falls plant attracted electric furnace industries, continually producing such things as aluminum, abrasives, silicon and graphite. Previously the electrochemical processes involved in these industries had been too expensive for large-scale use, but cheap power now made them practical. These new industries in turn provided the constant demand for power which was to make the Niagara project even more profitable than had originally been expected.

SG 15.17

The first transmission of power to Buffalo took place in November 1896. By 1899, there were eight 5,000-horsepower units in operation at Niagara, and the stockholders of the Cataract Construction Company had earned a profit of better than 50% on their investment. By this time the electrochemical industries, which had not figured in the original plans at all, were using more power than lighting and motors together.

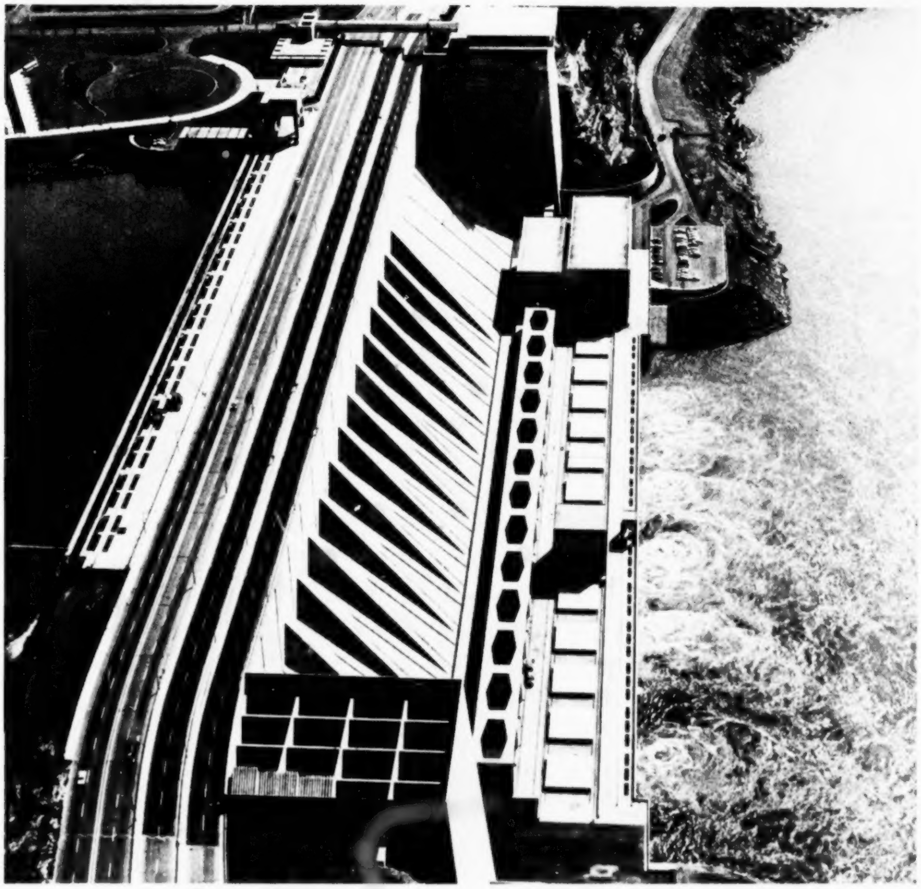
Wilson Dam (Tennessee Valley Authority), Alabama

As a postscript to the story of ac versus dc, it should be mentioned that dc is now coming back into favor for long-distance transmission of electric power at very high voltages. The reasons for this turnabout are explained in an article, "The future of direct current power transmission," reprinted in the Unit 4 Reader.

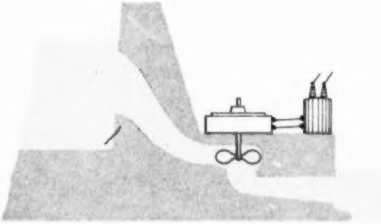
Why is it more economical to transmit electric power at high voltage and low current than at low voltage and high current?

Why won't transformers operate with steady dc?

Niagara Power Plant



The general principle of hydroelectric power generation is shown in this sketch: water flowing from a higher to lower level turns turbine blades attached to a generator shaft. The details of construction vary widely.



15.9 Electricity and society. Many times during the last hundred years, enthusiastic promoters have predicted that a marvelous future is in store for us. We need only stand back and watch the application of electricity to all phases of life. First of all, the backbreaking physical labor that has been the lot of 99% of the human race throughout the ages will be handed over to machinery run by electricity; the average citizen will have nothing more to do except push buttons for a few hours a day, and then go home to enjoy his leisure. Moreover, the old saying that "a woman's work is never done" will be forgotten, since electric machines will do all the cleaning, laundering and ironing, preparation of food and washing of dishes.

A second social purpose of electricity was conceived by President Franklin D. Roosevelt and others who believed that country life is more natural and healthy than city life. They saw that the steam engine had provided a source of power that could take over most work done by humans and animals, but only at the price of concentrating people in cities. But now that electrical transmission of power was possible, people could go back to the country without sacrificing the comforts of city life. One of the major achievements of Roosevelt's administration in the 1930's was the rural electrification program, which provided loans for rural cooperatives to install their own electrical generating and distribution systems in areas where the private power companies had previously found it unprofitable to operate. Federal power projects such as the Tennessee Valley Authority also assisted the campaign to make electricity available to everyone. By making country life more luxurious and reducing the physical labor involved in farming, electrification should have reversed the migration of people from rural to urban areas.

See the "Letter from Thomas Jefferson" in Project Physics Reader 4.

A third effect of electricity might be to unite a large country into a single social unit by providing rapid transportation and even more rapid communication between the different parts. To mention a frequently cited analogy: the dinosaur became extinct because his communication system was not adequate for such a large organism. Human society evolves much as the biological organisms: all parts develop in step and increase their interdependence. It follows that telephone communications and modern civilization had to develop together. The telephone would be necessary only in a complicated society and, as is now recognized, a complicated society cannot operate without a communications system something like the telephone.

See "The Electronic Revolution" in Project Physics Reader 4.

Having taken care of these problems for a large part of the population—getting work done, acquiring a more healthful environment, finding out what's going on and being able to do something about it—man now comes face to face with a new problem, or rather, a problem that was encountered before by only a tiny fraction of the world's population. Thanks to advances in science and technology, we no longer have to spend almost all of our time working for the bare necessities of life. Now, what is it that we really want to do? Whatever it might be, electricity might help us do it better. With electric lighting, we can read books at night, or attend large meetings, plays and concerts in public buildings. None of these things were impossible before electrical illumination was developed, but candles and gas lamps were messy, hard on the eyes, and (when used on a large scale) expensive and hazardous. With the telegraph, telephone, radio and television we can quickly learn the news of events throughout the world, and benefit from exchanging facts and opinions with other people.

See the article on "High Fidelity" in Project Physics Reader 4.

A cynical opinion. Wonderful as all this seems, a skeptic might take a much dimmer view. He might argue, for example, that by exploiting the resources of fossil fuel (coal, oil and gas) on his planet to do his work for him, man has used up in only 200 years most of the reserves of chemical energy that have been accumulated over the last two hundred million years. Our skeptic might claim that man has created a social system in which the virtues of honest toil and pride of workmanship have begun to be endangered by a working life of monotonous triviality for much of the population and chronic unemployment for some of the rest. The rise in the standard of living and acquisition of new gadgets and luxuries by many of those living in the rich industrial countries have not brought tranquility of spirit, but often only created a demand for more and more material possessions. Meanwhile the less fortunate citizens of the world, separated more and more from the rich countries that exploited them, look on in envy and anger.

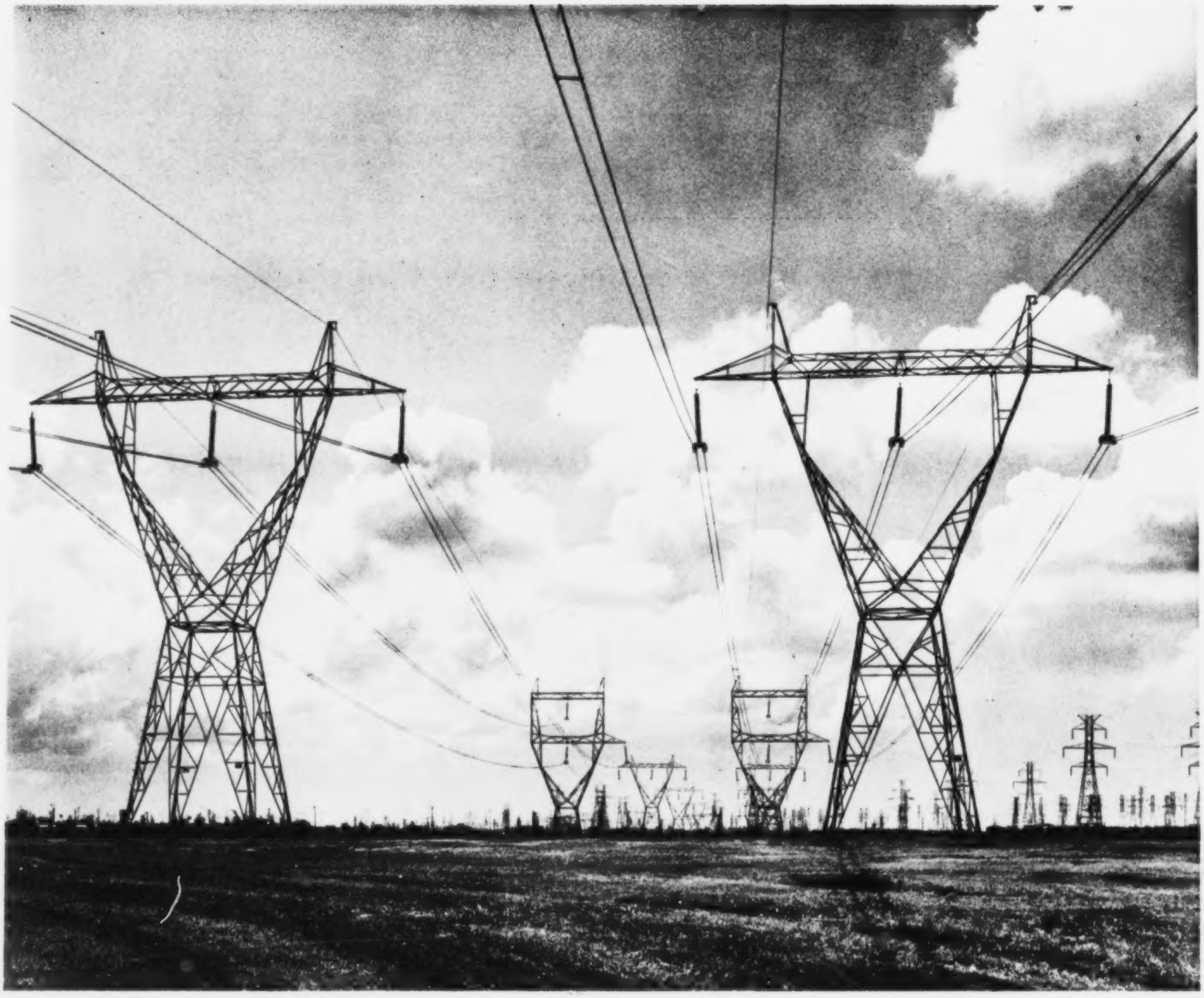
As for the labor-saving devices sold to the modern housewife, have they really made things any easier for her? The housewives in upper- and middle-income families work just as much as before, for what appliances now do used to be done by servants, perhaps better. The social changes that accompanied industrialization and electrification have also generated many new jobs for untrained women, and these jobs are more attractive than domestic service. Families with low incomes, if they can afford to buy just one major electrical appliance usually don't choose labor saving gadgets but a television set—and much of what comes out of that, our skeptic says, contributes nothing to a better life!

The decentralization of population which electricity was supposed to produce has come about but in an unexpected way. The upper- and middle-income inhabitants of cities have indeed been able to escape to the suburbs where they still enjoy all the convenience and pleasures of the electrical age. But they have left behind them urban ghettoes crowded with minority groups whose frustration at being deprived of the benefits of the "affluent society" is only aggravated by the scenes of suburban life presented to them on television. As for the farmer, modern technology has made his fields so productive that he sometimes works himself out of a job.

Electrical communications and rapid transcontinental transportation have bound us into a close-knit interdependent social system. But this has its disadvantages too. Thus, an unforgiving electronic computer may dredge up all a man's past mistakes when he applies for a job.

The interdependence of our modern electrical civilization was dramatically demonstrated at about 5 p.m. on November 9, 1965, when a faulty electrical relay in Canada caused a power failure and total blackout throughout most of the northeastern part of the United States. The only towns in New England that had electric lights that night were the ones whose independent electrical systems had refused to tie into the interstate power grid.

Electricity: good or bad? The point of such criticism is that it illustrates the other half of the total story: electricity, like any other area of scientific discovery and technological improvement, is neither good nor bad by itself. Electricity increases enormously the possibilities open to us, but we still have to choose among them. The decisions about the large-scale applications of electricity cannot be left to the experts in physics or engineering, or to the public utility companies, or to government agencies. They must be thrashed out by citizens who have taken the trouble to learn something about the physical forces that play such an important role in modern civilization—whether in the field of electrification, or the coming large-scale use of nuclear power, or the introduction of automation and other uses of computers, or whatever lies over the horizon. SG 15.19



Electric power lines in New York State

15.1 What sources of energy were there for industry before the electrical age? How was the energy transported to where it was needed?

15.2 Oersted discovered that a magnetic needle was affected by a current. Would you expect the magnetic needle to exert a force on the current? Why? How would you detect this force?

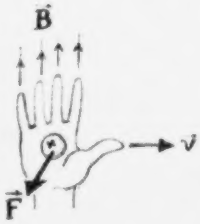
15.3 In which of these cases does electromagnetic induction occur?

a) A current is started in a wire held near a loop of wire.
b) A current is stopped in a wire held near a loop of wire.
c) A magnet is moved through a loop of wire.
d) A loop of wire is held in a steady magnetic field.
e) A loop of wire is moved across a magnetic field.

15.4 How do the conditions for the induction of currents by magnetic fields differ from those for the production of magnetic fields by currents?

15.5 Refer to the simple ac generator shown on p. 84. Suppose the loop is being rotated counter clockwise and we consider the segment b as it is pictured in the third drawing, moving down across the magnetic field.

A useful rule: if your fingers point along $\vec{B}$, and your thumb along $\vec{v}$, $\vec{F}$ will be in the direction your palm would push. For pos. charges use the right hand, and for neg. use the left hand.



a) Use the hand rule to determine the direction of the current induced in b.
b) The induced current is an additional motion of charges across the magnetic field, thus an additional magnetic force acts on segment b. Use the hand rule to determine the direction of the additional force, but before doing so try to guess the direction of the force.
c) Determine the direction of the additional force on charges in the segment labeled a, which is moving upwards across the field.

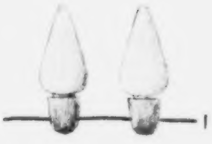
15.6 Why should a generator coil be much harder to rotate when it is connected to a load, such as a lamp, than when it is disconnected from any load?

15.7 Suppose two bar magnets, each held by one end at the same level but a few feet apart, are dropped so that one of them passes through a closed loop of wire. Which magnet reaches the ground first? Why?

15.8 Sketch a current of charges in a wire perpendicular to a magnetic field and use the hand rule to find the direction of force on the current. Imagine the wire moves sideways in response to the force. This sideways motion is an additional motion across the field and so each charge in the wire experiences an additional force. In what direction is the additional force on the charges?

15.9 Connect a small dc motor to a battery through a current meter. By squeezing on the motor shaft, vary the speed of the motor. On the basis of your answer to question 15.8, can you explain the effect that motor speed has on the current?

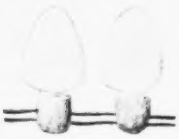
15.10 A dozen Christmas tree lights are connected in series and plugged into a 120-volt wall outlet.



a) If each lamp dissipated 10 watts of heat and light energy, what is the current in the circuit?
b) What is the resistance of each lamp?
c) What would happen to these lamps if they were connected in parallel across the 120-volt line? Why?

15.11 Suppose we wanted to connect a dozen 10-watt lamps in parallel across a 120-volt line. What resistance must each lamp have in this case? To determine the resistance, proceed by answering the following questions:

a) What current will there be in each lamp?
b) What is the resistance of each lamp?



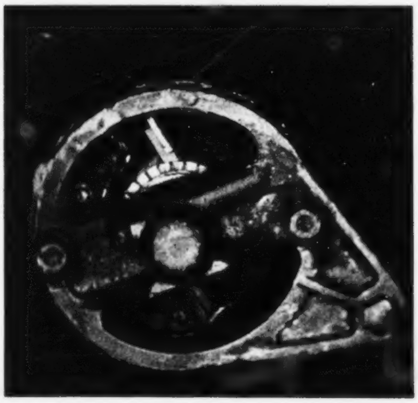
Compare the total current for this string of 10-watt lamps with the total current in the string of lamps in the previous question.

15.12 A man who built his own boat wanted to equip it with running lights and an interior light, but was puzzled about whether he should install a 6-volt system or a 12-volt system. He finally decided to use the 12-volt system because he reasoned that for given power (wattage) of light he would have less heating losses in the connecting wires if he used the higher voltage system. Let us see if his reasoning is correct. Suppose that his interior lamp is to be a 6-watt lamp. (A 6-watt lamp designed for use in 6-volt systems has a resistance of 6 ohms, but if designed for use in 12-volt systems a lamp has a resistance of 24 ohms.) The connecting wire has a resistance of 1/5 ohm.

a) If it were to operate at its full 6-watt rating, what current would the lamp require in each of the two systems?
b) If the currents calculated in (a) were the actual currents, what power loss would there be in the connecting wires in each case? Was his reasoning correct?
c) Because of the resistance of the connecting wires, the lamps described will not actually operate at full capacity. Recalculate parts (a) and (b) to determine what would be the actual currents, power losses, and power consumptions of the lamps.

15.13 A transformer for an electric train is used to "step-down" the voltage from 120 volts to 6 volts. The output power from the secondary coil is not much less than the input power to the primary coil. Suppose the current in the primary coil were ½ amp, what would be the current in the secondary coil if the input power and output power were the same?

15.14 For a transformer, the ratio of the secondary voltage to the primary voltage is the same as the ratio of the number of turns of wire on the secondary coil to the number of turns of wire on the primary coil. If a transformer were 100 per cent efficient, the output power would equal the input power; assume such is the case and derive an expression for the ratio of the secondary current to the primary current in terms of the turn ratio.



Multiple commutator segments of an automobile generator.

15.15 On many transformers thicker wire is used for one of the coils than for the other. Which would you expect has the thicker wire, the low-voltage coil or the high-voltage coil?

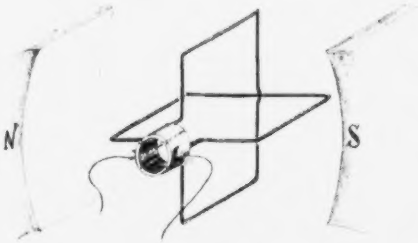
15.16 Comment on the advisability of getting out of a car over which a high-voltage power line has fallen.

15.17 What factors made Edison's recommendation for dc for the Niagara Falls system in error?

15.18 Write a report comparing the earliest electric automobiles with those being developed now.

15.19 What were some of the major effects of electricity on society?

15.20 It was stated on p. 85 that the output of a dc generator can be made smoother by using multiple windings. If each of two loops were connected to commutators as shown in the margin, what would the output current of the generator be like?



Chapter 16 Electromagnetic Radiation

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Radio telescope in Alaska framed by the Northern Lights

16.1 Introduction. On April 11, 1846, a distinguished physicist, Sir Charles Wheatstone, was scheduled to give a lecture at the Royal Institution in London. Michael Faraday, who frequently gave the Friday evening lectures at the Royal Institution, was prepared to introduce Wheatstone to the expectant audience of fashionable ladies and gentlemen. But at the last minute, just as Faraday and Wheatstone were about to enter the lecture hall, Wheatstone got stage fright, turned around and ran out into the street. Because Faraday felt obliged to give the lecture himself we now have on record some of Faraday's speculations which, as he later admitted, he would never have made public had he not suddenly been forced to speak for an hour.

Charles Wheatstone (1802-1875) made notable contributions to the sciences of acoustics, light and vision, and electricity; he invented the telegraph and the concertina.

Faraday, ordinarily so careful to confine his remarks to his experiments and observations, used this occasion to disclose his speculations on the nature of light. They can best be understood if we recognize that Faraday, like Oersted before him, believed that all the forces of nature are somehow connected. Electricity and magnetism, for example, could not be separate things that just happen to exist in the same universe; they must really be different forms of the same basic force. This metaphysical conviction, coming out of the speculations of Schelling and other German nature philosophers at the beginning of the nineteenth century, had inspired Oersted to search in the laboratory for a connection between electricity and magnetism. Eventually he found it in his discovery that an electric current in a conductor turns a nearby magnet. Faraday too, had been guided by a belief in the unity of natural forces.

SG 16.1

Could light also be considered another form of this basic "force?" Or rather, to ask the question using more modern terminology, is light a form of energy? If so, scientists should be able to demonstrate experimentally its connection with other forms of energy such as electricity and magnetism. Faraday did succeed in doing just this in 1845, when he showed that light traveling through heavy glass had its plane of polarization rotated by a magnetic field applied to the glass.

Having convinced himself by this experiment that there is a definite connection between light and magnetism, Faraday could not resist going one step further in his impromptu lecture the following year. He suggested that perhaps light itself is a vibration of magnetic lines of force. If two charged or magnetized objects are connected by an electric or magnetic line of force, then if one of them moves, a disturbance would be transmitted along the line of force. As

Faraday pointed out, if we assume that light waves are vibrations of lines of force, then we do not need to imagine that space is filled with an elastic substance, the ether, in order to explain the propagation of light. The lines of force could replace the ether, if we could show that lines of force have the elastic properties needed for wave transmission.

Faraday could not make this idea more precise because he lacked the mathematical skill needed to prove that waves could be propagated along lines of electric or magnetic force. Other physicists in Britain and Europe who might have been able to develop a mathematical theory of electromagnetic waves did not understand Faraday's concept of lines of force, or at least did not consider them a good basis for a mathematical theory. It was not until ten years later that James Clerk Maxwell, a Scottish mathematical physicist who had just completed his B. A. degree at Cambridge University, saw the value of the idea of lines of force and started using mathematics to express Faraday's concepts.

16.2 Maxwell's formulation of the principles of electromagnetism.

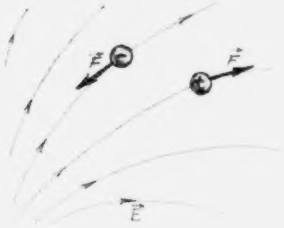
The work of Oersted, Ampère, Henry and Faraday established two basic principles of electromagnetism:

1. An electric current in a conductor produces magnetic lines of force that circle the conductor;

2. When a conductor moves across magnetic lines of force, a current is induced in the conductor.

The lines representing magnetic lines of force give the direction of the force on a magnetic north pole.

The lines representing electric lines of force give the direction of the force on a positive charge.



James Clerk Maxwell, in the 1860's, developed a mathematical theory of electromagnetism in which he generalized these principles so that they applied to electric and magnetic fields in conductors, in insulators, even in space free of matter.

Maxwell proceeded by putting Faraday's theory of electricity and magnetism into mathematical form. In 1855, less than two years after completing his undergraduate studies, Maxwell presented to the Cambridge Philosophical Society a long paper entitled, "On Faraday's Lines of Force." Maxwell described how these lines are constructed:

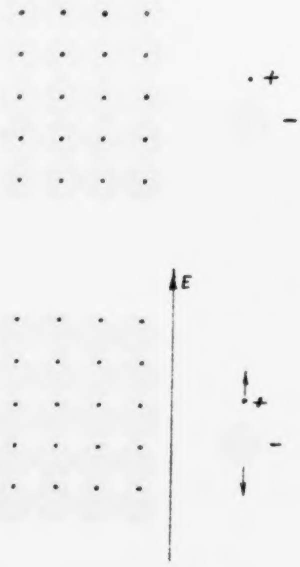
> ...if we commence at any point and draw a line so that, as we go along it, its direction at any point shall always coincide with that of the resultant force at that point, this curve will indicate the direction of that force for every point through which it passes, and might be called on that account a line of force. We might in the same way draw other lines of force, till we had filled all space with curves indicating by their direction that of the force at any assigned point.

Maxwell stated that his paper was designed "to show how, by a strict application of the ideas and methods of Faraday, the connection of the very different orders of phenomena which he has discovered may be clearly placed before the mathematical mind." In later papers during the next ten years Maxwell created his own models of electric and magnetic induction, expressed these models in mathematical form, and went on to add an entirely new idea of far-reaching consequences: an electric field that is changing with time generates a magnetic field. Not only currents in conductors, but changing electric fields in insulators such as glass or air or the ether are accompanied by magnetic fields.

See Maxwell's discussion "On the Induction of Electric Currents" in Project Physics Reader 4.

It is one thing to accept this newly stated connection between electric and magnetic fields; it is another task, both harder and more fun, to understand the physical necessity for such a connection. The next paragraphs are intended to make it seem reasonable and to give some notion how Maxwell came to propose that a changing electric field is accompanied by a magnetic field.

An insulator (glass, wood, paper, rubber) contains equal amounts of negative and positive charge (Sec. 14.3). In the normal state these charges are distributed so that the net charge in every large region of the material is zero. When these charges are subjected to electrical forces by placing the insulator in an electric field, the positive charges are pushed in one direction, the negative in the opposite direction. None of the charges in an insulating material (in contrast to a conductor) is free to move through the matter; the charges can only be displaced a small distance before the restoring forces in the insulator balance the force due to the electric field. The small displacement of charges that accompanies a changing electric field in an insulator constitutes a current. This current Maxwell called the displacement current. Maxwell assumed that this displacement current is just as effective in producing a magnetic field as a conduction current of the same magnitude. In an insulator the current of charges undergoing a displacement is directly proportional to the rate at which the electric field is changing in time. Thus the magnetic field that circles the displacement current can be considered a consequence of the time-varying electric field. If it is assumed that this model developed for matter can be applied to space free of matter (an apparently absurd idea that works) it follows that, under all circumstances an electric field that is changing with time generates a magnetic field.

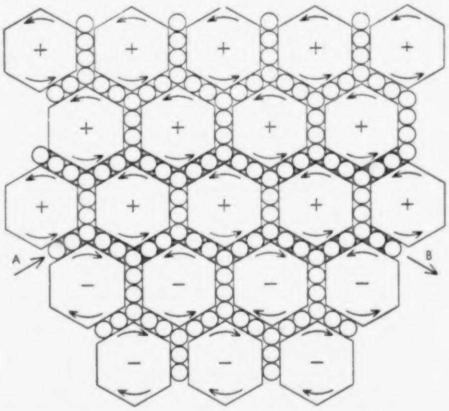


When an electric field is established in an insulating material, the + and - charges, which are bound to one another, are displaced. The displacement constitutes a current. (+ charges are represented by dots, and - charges by shaded circles.)

SG 16.2

16.2

In developing his electromagnetic theory Maxwell devised a mechanical model that provided the connections among the electrical and magnetic quantities observed experimentally by Faraday and others. Maxwell expressed the operation of the model in a group of equations. He found that his model and the equations representing the model suggested effects that had not yet been observed, such as the magnetic field of a displacement current. Once he found the sought-for relations between the electric and magnetic fields, he was free to discard the mechanical model.



Maxwell's drawing of his mechanical model of the ether. The magnetic field is represented by rotating "cells" (hexagons in the diagram) and electric charges are represented by ball bearings between the cells.

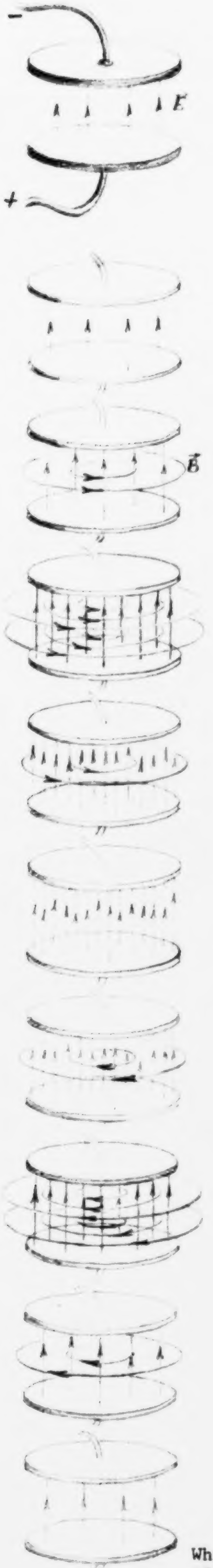
The intricate models devised by Maxwell and other British physicists were considered inappropriate, or worse, by many French scientists. Pierre Duhem, for example, remarked after reading about these models, "We thought we were entering the tranquil and neatly ordered abode of reason, but we find ourselves in a factory."

Maxwell later described the route he had followed from experiments, to a mechanical model, to a mathematical theory. In his paper of 1864 that summarized his work on electromagnetism, he wrote:

> I have on a former occasion attempted to describe a particular kind of motion and a particular kind of strain, so arranged as to account for the phenomena. In the present paper I avoid any hypothesis of this kind; and in using such words as electric momentum and elasticity in reference to the known phenomena of the induction of currents and the [displacement of charge in insulators], I wish merely to direct the mind of the reader to mechanical phenomena which will assist him in understanding the electrical ones. All such phrases in the present paper are to be considered illustrative not as explanatory.

According to Maxwell's theory, the basic principles of electromagnetism must be expanded to include the following:

1. A changing electric field produces a magnetic



When the electric field $\vec{E}$ between a pair of charged plates starts to increase in intensity, a magnetic field $\vec{B}$ is induced. The faster $\vec{E}$ changes, the more intense $\vec{B}$ is. When $\vec{E}$ diminishes, a $\vec{B}$ field is again induced, in the opposite direction.

field. The induced magnetic field vector $\vec{B}$ is at right angles to the electric field vector $\vec{E}$. The magnitude of $\vec{B}$ depends on position and on the rate at which $\vec{E}$ is changing. (See the diagrams on the opposite page.)

2. A changing magnetic field produces an electric field. The induced electric field vector $\vec{E}$ is at right angles to the magnetic field vector $\vec{B}$. The magnitude of $\vec{E}$ depends on position and on the rate at which $\vec{B}$ is changing. (See the diagrams on this page.)

As an illustration of the first principle, consider a pair of conducting plates connected to a source of current. As charges are moved onto the plates through the conductors connecting them to the source, the electric field in the space between the plates changes with time. This changing electric field produces a magnetic field that varies with distance from the region between the plates.

The first principle was a new prediction of Maxwell's. Previously it was thought that the only current that produced a magnetic field was the current in a conductor. The additional magnetic field that Maxwell said would arise from a changing electric field is so small in comparison to the magnetic field produced by the current in the conductors that it was not possible to measure it directly. But, as we shall see, Maxwell predicted consequences that *could* be tested.

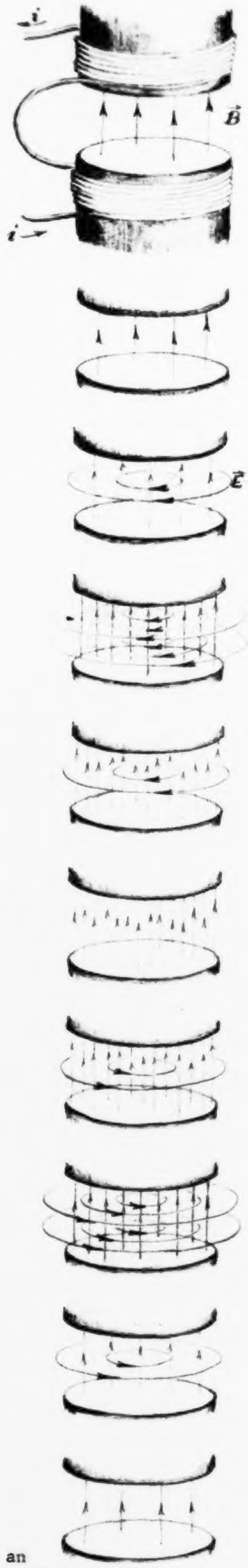
As an illustration of the second principle, which was known before Maxwell's work, consider the changing magnetic field produced by, say, increasing the current in an electromagnet. This changing magnetic field induces an electric field in the region around the magnet. If a conductor is aligned in the direction of the induced electric field, the free charges in the conductor will move under its influence, producing a current in the direction of the induced field. This electromagnetic induction was discovered experimentally and explained by Faraday.

To see how Maxwell's ideas were tested we must consider his prediction of waves of a new type—electromagnetic waves.

Q1 What did Maxwell propose is generated by a changing electric field?

Q2 What is a displacement current?

Q3 What did Maxwell's model help him find?



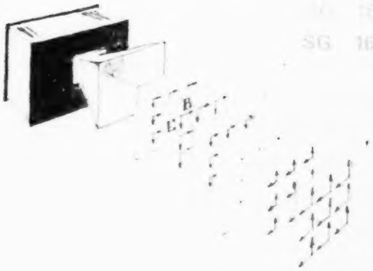
When the magnetic field $\vec{B}$ between the poles of an electromagnet starts to increase, an electric field $\vec{E}$ is induced. The faster $\vec{B}$ changes, the more intense $\vec{E}$ is. When $\vec{B}$ diminishes, an $\vec{E}$ field is again induced, in the opposite direction.

See "The Relationship of Electricity and Magnetism" in Project Physics Reader 4.

16.3 The propagation of electromagnetic waves. Suppose we create, in a certain region of space, electric and magnetic fields that change with time. According to Maxwell's theory, when we create an electric field $\vec{E}$ that is different at different times, this field will induce a magnetic field $\vec{B}$ that varies with time and with distance from the region where we created the changing electric field. In addition, the magnetic field that is changing with time induces an electric field that changes with time and with distance from the region where we created the magnetic field.

Actually, the electric and magnetic field changes occur together, much like the "action" and "reaction" of Newton's third law.

This reciprocal induction of time- and space-changing electric and magnetic fields makes possible the following unending sequence of events. A time-varying electric field in one region produces a time- and space-varying magnetic field at points near this region. This magnetic field produces a time- and space-varying electric field in the surrounding space. This electric field, in turn, produces time- and space-varying magnetic fields in its neighborhood, and so on. An electromagnetic disturbance initiated at one location by vibrating charges as in a light source or the transmitter of a radio or television station, can travel to distant points through the mutual generation of the electric and magnetic fields. The electric and magnetic fields "join hands," so to speak, and "march off" through space in the form of an electromagnetic wave.



SG 16.3
SG 16.4

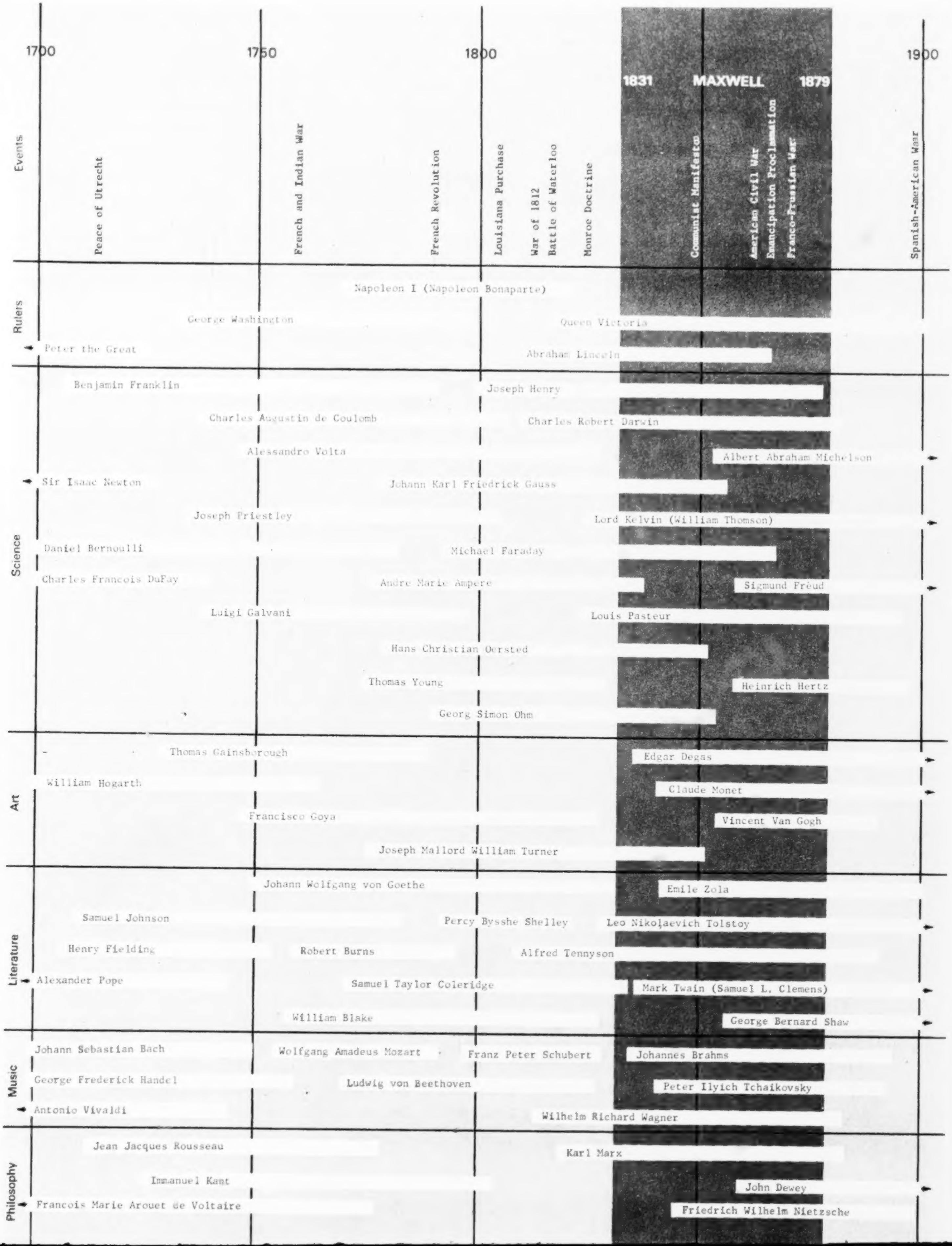
In Chapter 12 it was shown that waves occur when a disturbance created in one region produces at a later time a disturbance in adjacent regions. Snapping one end of a rope produces, through the action of one part of the rope on the other, a displacement at later times at points further along the rope. Dropping a pebble into a pond produces a disturbance that moves away from the source as a result of the action of one part of the water on the neighboring parts. Time-varying electric and magnetic fields produce a disturbance that moves away from the source as the varying fields in one region create varying fields in neighboring regions.

What determines the speed with which the electromagnetic waves travel? In the case of waves in a rope, or in water, the speed of propagation is determined by the stiffness, or force which a displaced part of the material exerts on adjacent parts, and by the density of the material. Speed increases with increasing stiffness, but decreases with increasing density. Indeed the same relation between wave speed, stiffness, and density holds for both of these mechanical wave motions, and for many other types of waves. Maxwell,

As was stated in Unit 3, page 118, the speed of propagation depends on both the stiffness and density of the medium:

$$v=\sqrt{\frac{E}{d}},$$

where v is the wave speed, E is the elasticity (measure of stiffness), and d is the density.


1700
1750
1800
1900
1831
MAXWELL
1879
Events
Peace of Utrecht
French and Indian War
French Revolution
Louisiana Purchase
War of 1812
Battle of Waterloo
Monroe Doctrine
Communist Manifesto
American Civil War
Emancipation Proclamation
Franco-Prussian War
Spanish-American War
Rulers
Napoleon I (Napoleon Bonaparte)
George Washington
Queen Victoria
Peter the Great
Abraham Lincoln
Science
Benjamin Franklin
Joseph Henry
Charles Augustin de Coulomb
Charles Robert Darwin
Alessandro Volta
Albert Abraham Michelson
Sir Isaac Newton
Johann Karl Friedrick Gauss
Joseph Priestley
Lord Kelvin (William Thomson)
Daniel Bernoulli
Michael Faraday
Charles Francois DuFay
Andre Marie Ampere
Sigmund Freud
Luigi Galvani
Louis Pasteur
Hans Christian Oersted
Thomas Young
Heinrich Hertz
Georg Simon Ohm
Art
Thomas Gainsborough
Edgar Degas
William Hogarth
Claude Monet
Francisco Goya
Vincent Van Gogh
Joseph Mallord William Turner
Literature
Johann Wolfgang von Goethe
Emile Zola
Samuel Johnson
Percy Bysshe Shelley
Leo Nikolaevich Tolstoy
Henry Fielding
Robert Burns
Alfred Tennyson
Alexander Pope
Samuel Taylor Coleridge
Mark Twain (Samuel L. Clemens)
William Blake
George Bernard Shaw
Music
Johann Sebastian Bach
Wolfgang Amadeus Mozart
Franz Peter Schubert
Johannes Brahms
George Frederick Handel
Ludwig von Beethoven
Peter Ilyich Tchaikovsky
Antonio Vivaldi
Wilhelm Richard Wagner
Philosophy
Jean Jacques Rousseau
Karl Marx
Immanuel Kant
John Dewey
Francois Marie Arouet de Voltaire
Friedrich Wilhelm Nietzsche

assuming that this relation would hold for electromagnetic waves, proceeded to compute the stiffness and density of electric and magnetic fields propagating through the ether. The hard problem was to find values for these two properties of the electric and magnetic fields.

Maxwell made his calculations in the following way. First, he showed that the part of the model that gives stiffness to the mechanism is the part that is analogous to the electric field. The part that determines the density is the part that is analogous to the magnetic field. Next, he proved mathematically that the ratio of these two factors, which determines the wave speed, is independent of the strength of the fields. Finally, Maxwell demonstrated a remarkable property of these electric and magnetic fields: the ratio of stiffness to density, and hence the speed of the waves, is neither zero nor infinite, the extreme values one might expect in space empty of matter, but a definite quantity that can be measured in the laboratory. Quite a trip from rotating rods and ball bearings to waves that travel through space free of matter!

Maxwell showed how the speed of electromagnetic waves could be calculated from laboratory experiments in which the same quantity of electric charge is measured by two different methods. One of the methods makes use of the Coulomb force that is proportional to the magnitude of the charge ($F \propto q$). The other method makes use of the magnetic force exerted on a charge moving in a magnetic field—the force that is proportional to the product of the magnitude of the charge and its speed ($F \propto qv$). The two calculated values for the charge are in different units, and their ratio has the units of speed.

The actual experiment involved discharging a Leyden jar through a sensitive moving-coil meter. One calculation of the amount of charge is made from the electric force exerted on a sphere charged from the Leyden jar. The second calculation is made from the deflection of the moving coil in the field of the meter's permanent magnet as the Leyden jar is discharged through it.

The necessary measurements had been performed in Germany five years earlier by Weber and Kohlrausch. Using their values Maxwell calculated that the speed of electromagnetic waves should be 310,740,000 meters per second. He was immediately struck by the fact that this large number was very close to another speed well known in physics. In 1849 Fizeau had measured the speed of light and obtained a value of 314,858,000 meters per second. The close similarity between these two numbers was, Maxwell felt, more than coincidence. It could have been a chance occurrence, but Maxwell, with faith in the rationality of nature, believed that there must be a deep underlying reason for these two numbers being the same, within the limits of experimental error. The critical significance for physics was obvious at once to him, and he wrote:

> The velocity of the transverse undulations in our hypothetical medium, calculated from the electromagnetic experiments of MM. Kohlrausch and Weber, agrees so exactly with the velocity of light cal- agrees so exactly with the velocity of light calculated from the optical experiments of M. Fizeau, that we can scarcely avoid the inference that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena.

Maxwell had shown that $\vec{E}$ and $\vec{B}$ are perpendicular to each other and to the direction of propagation of the wave. In the terminology of Chapter 12, electromagnetic waves are transverse; and as we noted in Chapter 13, it was known that light waves are also transverse.

By means of his generalized principles of electromagnetism, including the new idea that changing electric fields produce magnetic fields, Maxwell showed that electric and magnetic fields can propagate together as waves in space. The speed of propagation is the same as the speed of light.

Maxwell had not anticipated this agreement. In late 1861, he wrote in a letter to his friend Lord Kelvin:

> I made out the equations before I had any suspicion of the nearness between the two values of the velocity of propagation of magnetic effects and that of light, so that I think I have reason to believe that the magnetic and luminiferous media are identical.

The magnetic and luminiferous media were those ethers supposed to be responsible for transmitting, respectively, magnetic forces and light.

Realizing the great significance of his discovery, Maxwell turned his efforts to making the theory mathematically elegant and freeing it from his admittedly artificial model. In 1865, after he had shown that the equations of his theory could be derived from his general principles of electromagnetism without relying on special mechanical assumptions, Maxwell wrote to his cousin, Charles Cay:

> I have also a paper afloat, with an electromagnetic theory of light, which, till I am convinced to the contrary, I hold to be great guns.

The synthesis of electromagnetism and optics was a great event in physics. In fact, physics had known no greater time since the 1680's when Newton was doing his monumental work on mechanics. Although Maxwell's electromagnetic theory grew up in Maxwell's mind in a Newtonian framework, it leapt out of that framework and became the second great general physical theory, a theory independent of its mechanical origins. Like Newtonian mechanics Maxwell's electromagnetic field theory was spectacularly successful. We will see something of that success in the next few sections. The success went in two different directions: the practical and the conceptual. Practically it led to a whole host of modern developments, such as radio and television. On the conceptual level it led to a whole new way of viewing the universe. The universe was not a Newtonian machine of whirling parts; it included fields and energies that no machine could duplicate. As we will note later, Maxwell's work led almost directly to the special theory of relativity, and other physical theories were nourished by it. Maxwell's field theory not only synthesized electromagnetism and light, but provided a new way of looking at the world that made possible the flowering of physics in the twentieth century.

For a general survey of the development of physical ideas leading up to Maxwell's theory, see the article by Einstein and Infeld, "The Electromagnetic Field," in *Project Physics Reader 4*.

Q4 What ratio did Maxwell use in calculating the speed of electromagnetic waves?

Q5 What discovery did he make upon calculating this speed?

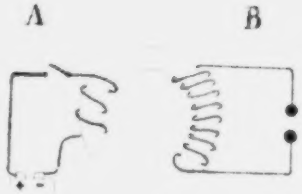
16.4 *Hertz's experiments*. Did Maxwell's theoretical result establish that light actually does consist of electromagnetic waves, or even that electromagnetic waves exist at all? No. Most other physicists remained skeptical for several years. The fact that the ratio of two quantities determined by electrical experiments came out equal to the speed of light certainly suggested that there is *some* connection between electricity and light; no one seriously argued that it was only a coincidence. But stronger evidence was needed before the rest of Maxwell's theory, with its mysterious displacement current, could be accepted.

What further evidence would be sufficient to persuade physicists that Maxwell's theory was correct? Maxwell showed that his theory could explain all the known facts about electricity, magnetism and light. But so could other theories. To a modern physicist who has learned Maxwell's theory from recent textbooks, the other theories that were proposed in the nineteenth century would all seem much more complicated and artificial. But at the time, Maxwell's theory used the strange idea of fields and was difficult to understand. On the basis of simplicity Maxwell's theory could not win out in the minds of those physicists who were not accustomed to thinking in terms of fields. It could only be accepted in preference to other theories if it could be used to predict some *new* property of electromagnetism or light.

Maxwell himself made two such predictions from his theory. Unfortunately, he did not live to see them verified experimentally, for he died in 1879 at the age of 48.

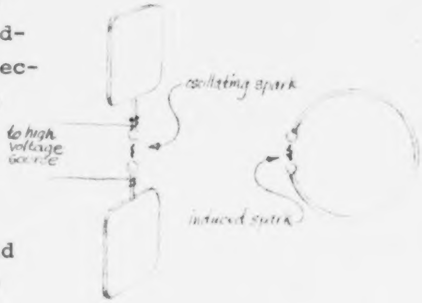
Maxwell's most important prediction was that electromagnetic waves of many different frequencies could exist. All such waves would be propagated through space at the speed of light. Light itself would correspond to waves of only a small range of frequencies, from 4×10^{14} cycles/sec to 7×10^{14} cycles/sec—frequencies that happen to be detectable by the human eye.

To test this prediction, it was necessary to invent some apparatus that could produce and detect electromagnetic waves of other frequencies than those of light. This was first done by the German physicist Heinrich Hertz. In 1886, Hertz noticed a peculiar effect produced by the sparking of an induction coil. It had already been observed by other scientists that sparks sometimes jumped through the air between the terminals of an induction coil. You will recall (Chapter 15) that an induction coil can be used to produce high voltages if there are many more turns of wire on one side than the other. Ordinarily, air does not conduct electricity, but when there is a very large potential difference between two wires a short distance apart, a conducting pathway may be formed momentarily by ionization of the air molecules, and a short burst of electricity may pass through. We see a spark as visible evidence of this quick motion of charge. Hertz observed that when a piece of wire was bent around so that there was a short gap between its two ends, and held near an induction coil, a spark would jump across the air gap in the wire when a spark jumped across the terminals of the induction coil.



Starting and stopping the current in coil A with a vibrating switch produces a rapidly changing magnetic field in the iron core. This rapidly changing field induces high voltage peaks in the many-turn coil B.

Each spark produced by an induction coil is actually a series of many sparks jumping rapidly back and forth between the terminals. Hertz could control the jumping frequency by changing the size and shape of the 16-inch square plates he used for terminals. He reasoned that as the sparks jump back and forth they must be setting up rapidly changing electric and magnetic fields in the air gap, and these fields, according to Maxwell's theory, will propagate through space as electromagnetic waves. (The frequency of the waves will be the same as the jumping frequency of the sparks.)



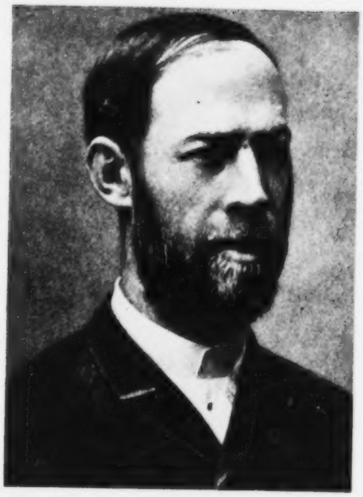
When the electromagnetic waves pass over the air gap in the bent piece of wire, they will set up rapidly changing electric and magnetic fields there. A strong electric field produces a spark in the air gap, just as a field originally produced a spark between the terminals of the induction coil. Since the field is rapidly changing, sparks will jump back and forth between the two ends of the wire. This wire serves as a detector of the electromagnetic waves generated by the induction coil.

SG 16.6

If Hertz's interpretation of his experiment is correct, and if the detector is really receiving electromagnetic waves which have traveled through space from the induction coil, then there must be a short time delay between the two sparks. The spark in the detector cannot occur at exactly the same instant as the spark in the induction coil because it takes a little time for the wave to go from one place to the other.

In 1888, Hertz was able to measure the speed of these electromagnetic waves and found that this speed, as Maxwell had predicted, is just the speed of light.

In subsequent experiments, Hertz showed that the electromagnetic radiation from his induction coil has all the usual properties of light waves. It can be reflected at the surface of a wall and by metallic conductors, and the angle of incidence is equal to the angle of reflection (see Sec. 13.3). The electromagnetic radiation can be focussed by a concave metallic mirror. It shows diffraction effects when it passes through an opening in a screen. It is refracted in passing through prisms of glass, wood, plastic and other non-conducting material.



Heinrich Hertz (1857-1894) was born in Hamburg, Germany. During his youth he was mainly interested in languages and the humanities but became interested in science after a grandfather gave him some apparatus. Hertz did simple experiments in a small laboratory which he had fitted out in his home. After completing secondary school (and a year of military service) he undertook the serious study of mathematics and physics at the University of Berlin in 1878. In 1883 he devoted himself to the study of electromagnetism, including the recent work of Maxwell. Two years later he started his famous experiments on electromagnetic waves. During the course of this work, Hertz made another discovery—the photoelectric effect—which has had a profound influence on modern physics. We shall study this effect in Chapter 18 (Unit 5).

Hertz's experiments provided dramatic confirmation of Maxwell's electromagnetic theory. They showed that electromagnetic waves actually exist, that they travel with the speed of light and that they have the familiar characteristics of light. There was now rapid acceptance of Maxwell's theory by mathematical physicists, who applied it with great success to the detailed analysis of a wide range of phenomena.

Maxwell also predicted that electromagnetic waves will exert a pressure on any surface that reflects or absorbs them. This pressure is very small, and experimentally it is extremely difficult to distinguish it from the pressure caused by air currents set up by heating of the surface that absorbs the waves. The technical difficulties involved in testing this prediction were not solved until 1899, when Lebedev in Russia and two years later, Nichols and Hull in the United States finally confirmed the existence of radiation pressure. They found that this pressure has exactly the value predicted by Maxwell's theory.

SG 16.7

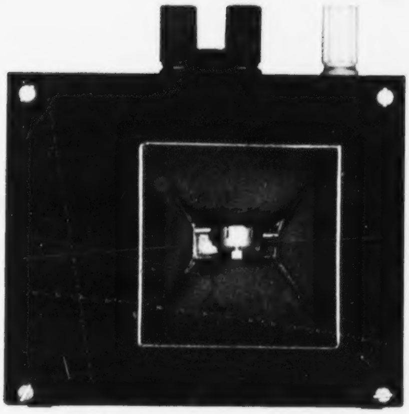
SG 16.8

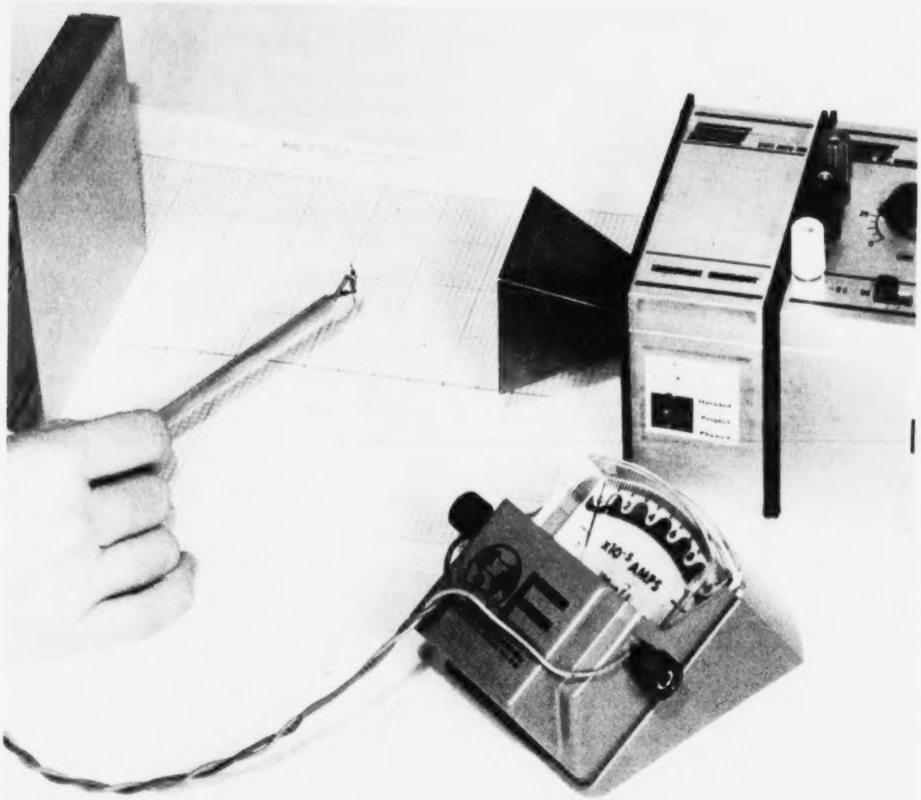
Thus, at the end of the nineteenth century, Maxwell's electromagnetic theory stood on the same level as Newton's laws of mechanics, as an established part of the foundations of physics.

Q6 What prediction of Maxwell's was verified by Hertz?

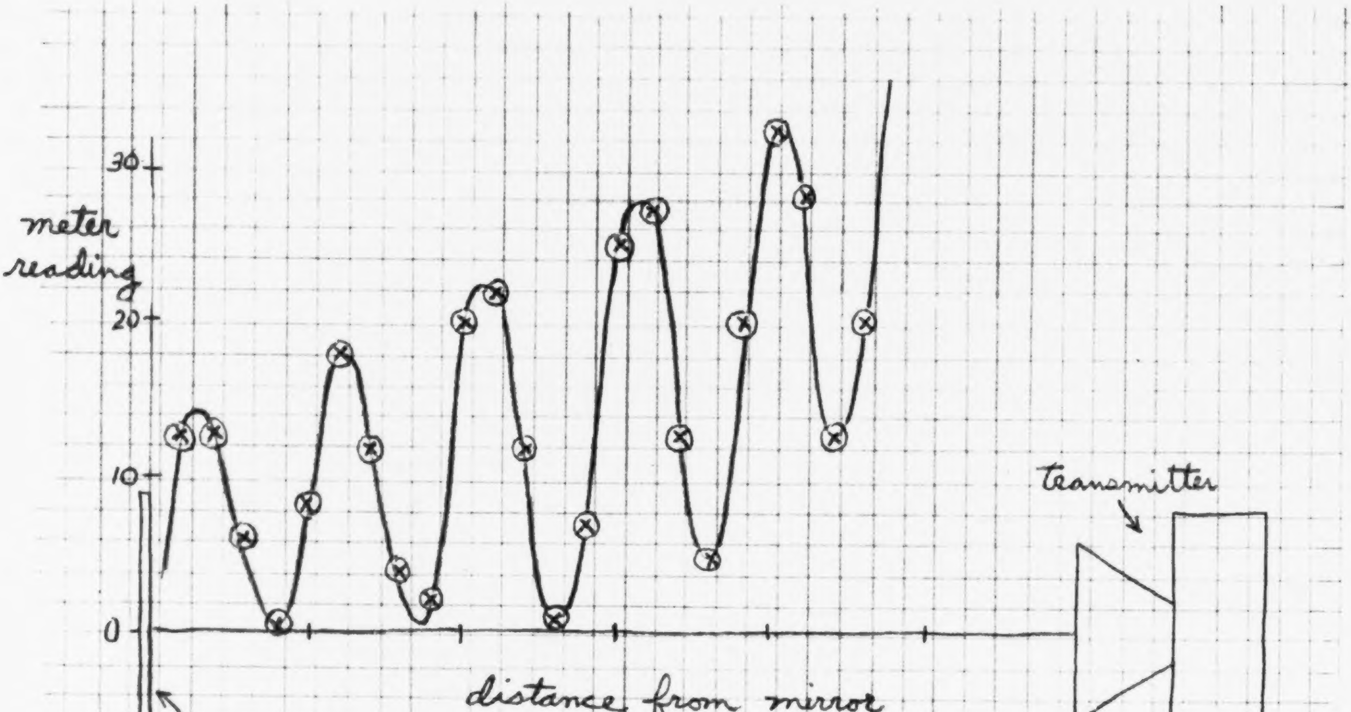
Q7 What did Hertz use as a detector of electromagnetic waves?

Q8 What second prediction of Maxwell's was later confirmed?





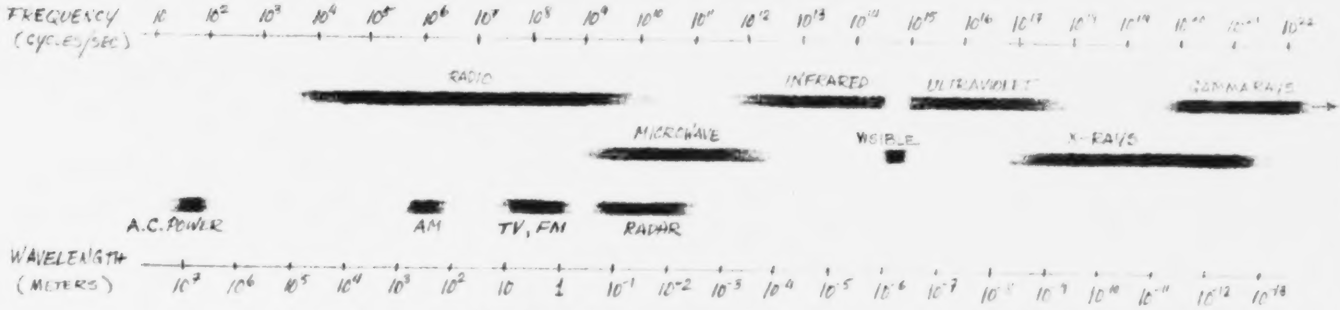
Electromagnetic radiation of a few centimeters wavelength is produced by oscillating electric fields inside the metal horn. Experiments with this radiation show phenomena similar to those observed for water and sound waves. Below are actual measurements of the intensity of a standing interference pattern in front of a flat reflecting surface. All these experiments can be done in your laboratory period.



The frequency unit "cycles/sec" is being replaced by the equivalent unit, the "Hertz." You will sometimes see the forms 10^6 Hertz, 10^6 cycles/sec, 10^3 kilocycles/sec, 1 megacycle/sec: all signifying the same frequency. Some FM radio stations now regularly give their frequencies in megahertz.

16.5 The electromagnetic spectrum. Hertz used radiation with a wavelength of about 1 meter, about a million times the wavelength of visible light. You might now ask: is this an isolated set of wavelengths or a small segment of a spectrum of much greater extent? Experiments show that there is a wide and continuous variation in the wavelength (and frequency) of electromagnetic waves; the entire possible range is called the electromagnetic spectrum. A range of frequencies from about 1 cycle/sec to 10^{25} cycles/sec, corresponding to a wavelength range from about 10^8 meters to 10^{-17} meters, has been studied and many frequency regions have been put to practical use.

Light, heat, radio waves and x rays are names given to certain regions in the electromagnetic spectrum. Each of these names denotes a region in which radiation is produced or observed in a particular way. For example, light may be perceived through its effect on the retina of the eye, but to detect radio waves we need electronic equipment to select and amplify the signal. The named regions overlap; for example, some radiation is called "ultraviolet" or "x-ray" depending on how it is produced.

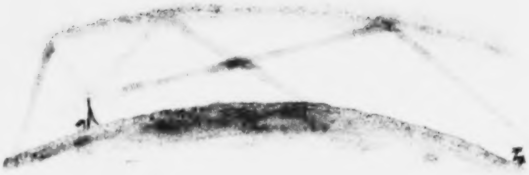

FREQUENCY (CYCLES/SEC)
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}
RADIO
INFRARED
ULTRAVIOLET
GAMMA RAYS
MICROWAVE
VISIBLE
X-RAYS
A.C. POWER
AM
TV, FM
RADAR
WAVELENGTH (METERS)
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}

SG 16.9

All the waves in the electromagnetic spectrum, although produced and detected in various ways, behave as predicted by Maxwell's theory. All electromagnetic waves travel through space at the same speed, the speed of light. They all carry energy; when they are absorbed the absorber is heated. Electromagnetic radiation, whatever its frequency, can be emitted only by a process in which energy is supplied to the source of radiation. There is now overwhelming evidence that electromagnetic radiation originates from accelerated charges. This acceleration may be produced in many ways: by heating materials to increase the vibrational energy of charged particles, by varying the charge on an electric conductor (an antenna), or by causing a stream of charged particles to change its direction. In these and other processes the work done by the force applied to the electric charges becomes the energy of radiation.

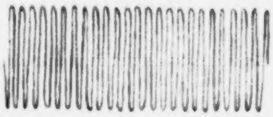
See "The Electronic Revolution" in Project Physics Reader 4.

Radio. Electromagnetic waves of frequencies of 10^4 to 10^7 cycles/sec are efficiently reflected by electrically charged layers in the upper atmosphere. This reflection makes it possible for radio waves to be detected at great distances from the source. Radio signals have wavelengths from tens to thousands of meters. Such waves can easily diffract around relatively small obstacles such as trees or buildings, but large hills and mountains may cast severe shadows.

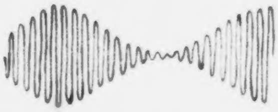


SG 16.10
SG 16.11

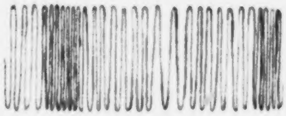
Radio waves that can traverse large distances, either directly or by relay, are very useful for conveying information. Communication is accomplished by changing the signal in some way following an agreed code that can be deciphered by the recipient. The first radio communication was achieved by turning the signal on and off in the agreed pattern of the Morse code. Later the amplitude of the signal was varied in accordance with the tones of speech or music. Still later the frequency of the signal was varied. In broadcast radio and television the decoding is done in the receiver and the loudspeaker or TV picture tube, so that the message takes the same form at the receiver that it had at the transmitter.



carrier wave



AM: information conveyed by amplitude modulation (variation) of the carrier



FM: information conveyed by frequency modulation (variation) of the carrier

Because electromagnetic signals can interfere with one another it is necessary to limit their transmission. The International Telecommunication Union (ITU) controls radio transmission and other means of international communication. Within the United States, the Federal Communications Commission (FCC) is the government agency that regulates radio transmission. In order to reduce the interference of one signal with another, the FCC assigns suitable frequencies to radio stations, limits their power or sometimes the power radiated in particular directions, and often restricts the hours of transmission.

SG 16.12
SG 16.13
SG 16.14

Television and radar. Television and FM broadcasting stations operate at frequencies of about 10^8 cycles/sec or wavelengths of about one meter. These frequencies are not reflected by the layers of electric charge in the upper atmosphere; the signals travel in nearly straight lines and pass into space instead of following the curvature of the earth. Coaxial cables or relay stations are necessary to transmit signals between points on the earth separated by more than about 50 miles. Signals can be transmitted from one continent to another by relay satellites.

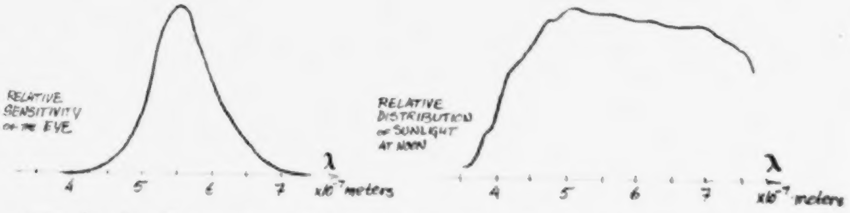
Satellites are used to relay microwaves all over the world. The microwaves can carry TV or telephone information.

These meter wavelength signals do not pass around objects, such as cars, ships, or aircraft, which have dimensions of several meters. The interference with the direct waves that results from reflection of these waves by passing airplanes can produce a very noticeable and annoying movement and flicker of the television picture. Signals of wavelength from one meter down to as short as one millimeter are used to detect aircraft and ships. If the transmission takes the form of pulses, the time from the radiation of a pulse to the reception of its echo measures the distance of the reflecting object. This technique is called RAdio Detection And Ranging, or RADAR. When a large antenna is used with waves of very short wavelength, a sharp beam like that of a searchlight can be produced. From the reflection of a sharp beam that is pulsed both the direction and distance of an object can be measured.

A photo taken in Utah with film sensitive only to infrared.

Infrared radiation. Electromagnetic waves with wavelengths from 10^{-1} to 10^{-4} meters are often called microwaves. It is difficult to construct circuits that oscillate at frequencies high enough to produce these waves. However, electromagnetic waves shorter than about 10^{-4} meters are emitted copiously by the atoms of hot bodies. This "radiant heat" is usually called infrared, because most of the energy is in the wavelengths slightly longer than the red end of the visible band of radiation. While associated mainly with heat radiation, they do have some properties which are the same as those of visible light. The shorter infrared waves affect specially treated photographic film, and photographs taken with infrared radiation show some interesting effects. Since scattering by small particles in the atmosphere is very much less for long wavelengths (Sec. 13.6), infrared will penetrate smoky haze dense enough to block visible light.

Visible light. The visual receptors in the human eye are sensitive to electromagnetic radiation with wavelengths between about 7×10^{-7} and 4×10^{-7} meters. Radiation of these wavelengths is usually called "light," or more explicitly, "visible light." The peak sensitivity of the eye is in the green and yellow, roughly the same as the peak of solar radiation which reaches the earth's surface.

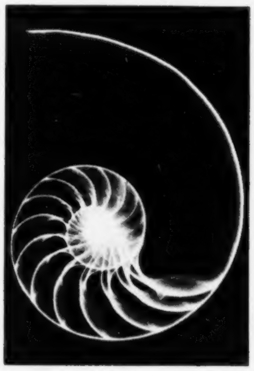


SG 16.20

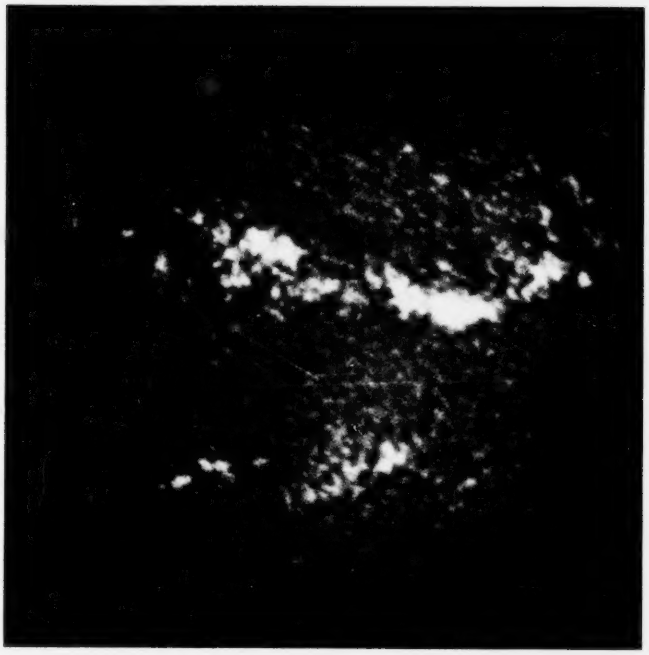
SG 16.21

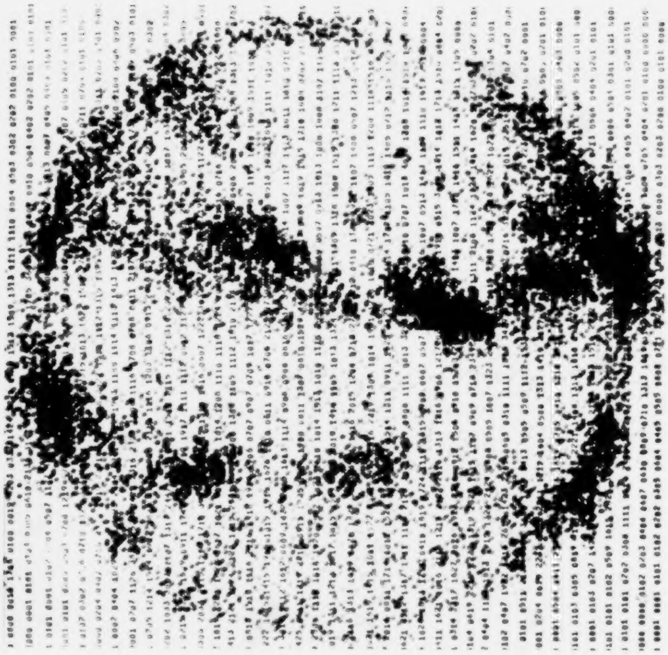
Ultraviolet light. Electromagnetic waves shorter than the visible violet are called ultraviolet. The ultraviolet region of the spectrum is of great interest to the spectroscopist because it includes the radiation characteristic of many kinds of atoms. Of more general interest is its ability to cause many kinds of photochemical reactions in which radiant energy is converted directly into chemical energy. Typical of these reactions are those which occur in silver bromide in the photographic process, in the production of ozone in the upper atmosphere and in the production of the dark pigment, known as melanin, in the skin.

X rays. This radiation (wavelengths from about 10^{-8} meters to 10^{-17} meters) is commonly produced by the sudden deflection or stopping of electrons when they strike a metal target. The maximum frequency of the radiation generated is determined by the energy with which the electrons strike the target, which is determined by the voltage through which they are accelerated (Sec. 14.8). So the maximum frequency increases with the accelerating voltage. The "harder" the x rays (the higher the frequency), the greater is their penetration of matter. The distance of penetration also depends on the nature of the material penetrated. X rays are quite readily absorbed by bone (which contains calcium), whereas they pass much more readily through lower density organic matter (such as flesh) containing mainly the light atoms hydrogen, carbon and oxygen. This fact, combined with the ability of x rays to affect a photographic plate, leads to some of the medical uses of x-ray photography. Because x rays can damage living cells they should be used with great caution and only by trained technicians. Some kinds of diseased cells are injured more easily by x rays than are healthy cells, and so carefully controlled x-ray beams can be used in therapy to destroy cancer or other harmful cells.


An x-ray photo of a chambered nautilus sea shell.

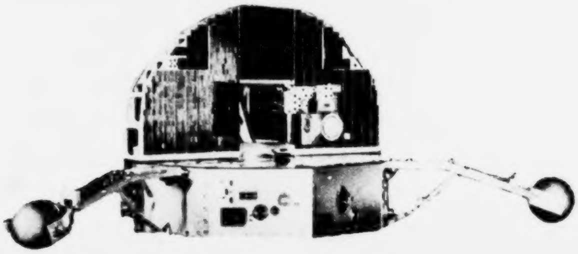
X rays produce interference effects in a special type of reflection which occurs when they fall on a crystal, in which atoms and molecules are arranged in a regular pattern. Successive reflections from crystal planes (parallel planes containing substantial numbers of atoms) lead to an interference pattern which can be used in either of two ways. If the spacing of the atoms in the crystal is known, the wavelength of the x rays can be calculated. Conversely, if the x-ray wavelength is known, the distance between crystal planes, and thus the structure of the crystalline substance, can be determined. X rays are now widely used by chemists and mineralogists seeking information about crystal structure.

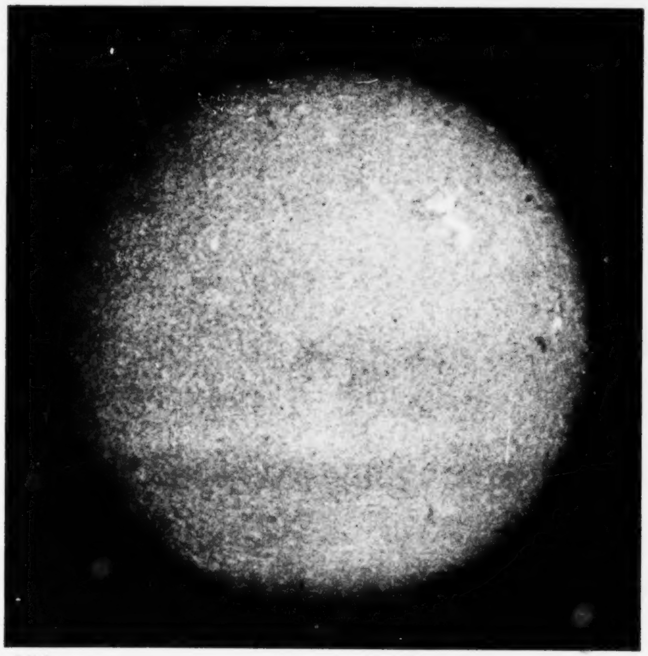


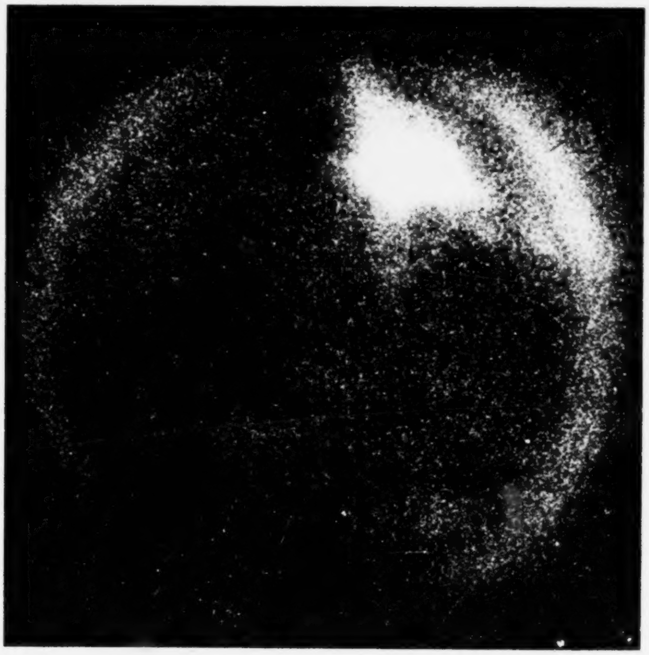


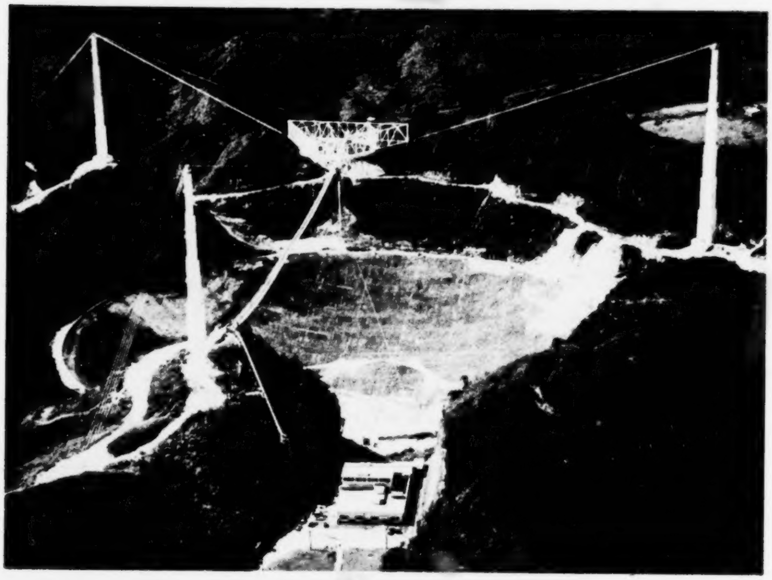
Astronomy Across the Spectrum

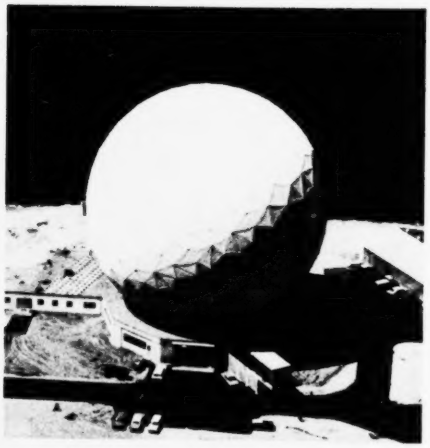
Electromagnetic radiation of different wavelengths brings us different kinds of information. Above are two views of the sun on Oct. 25, 1967: at the left is a photo taken in violet light; at the right is a computer plot of intensity of very short ultraviolet emission. The UV doesn't penetrate the earth's atmosphere; the information displayed here was collected by the Orbiting Solar Observatory satellite shown at the right. Below are three views of the sun on Mar. 17, 1965. At the left is a photograph in red light; at the right is an image formed by x rays; on the next page is an intensity contour map made from the image. The x-ray telescope was raised above the earth's atmosphere by an Aerobee rocket.

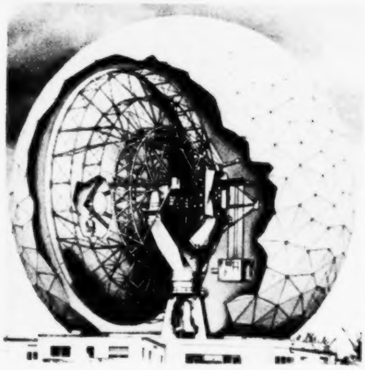




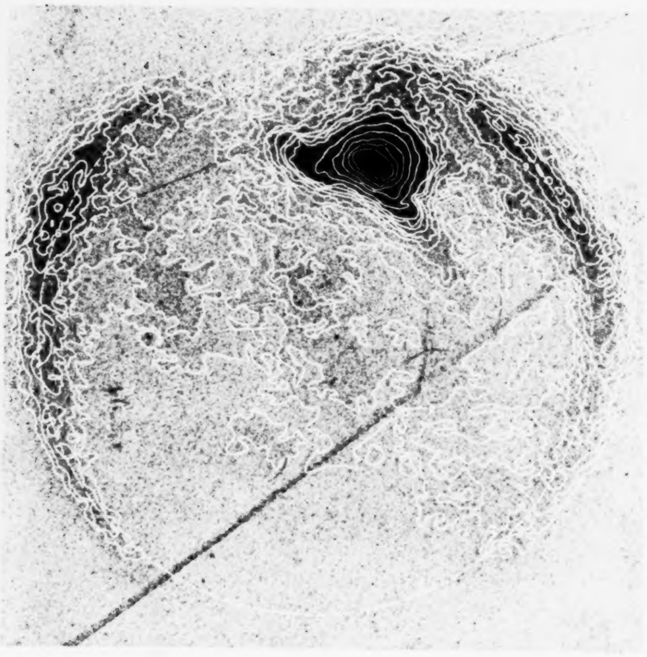


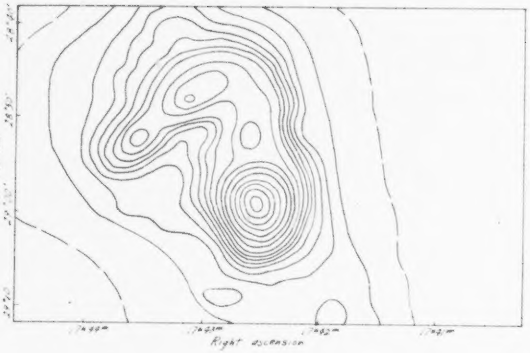


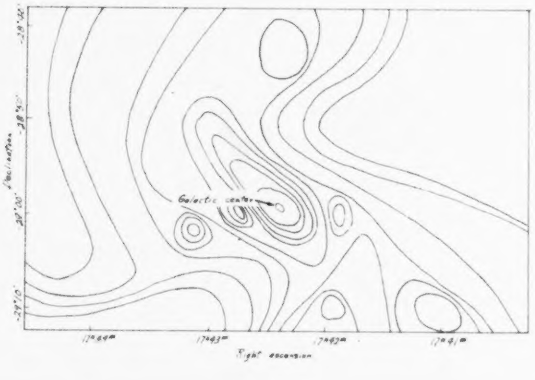




Longer-wavelength radiations such as radio and infrared are able to penetrate interstellar dust. Radio telescopes come in a great variety of shapes and sizes. Above is shown the huge Arecibo telescope in Puerto Rico; it has a fixed reflector but a moveable detector unit. To the right are a photograph and a diagram of a precise steerable antenna, the Haystack antenna in Massachusetts. Information collected with this instrument at 3.7 cm wavelength led to the upper contour map at right. This map of radio brightness is of the portion of the sky around the center of our galaxy; the area covered is about that of the full moon. The infrared brightness of the same portion of sky is shown in the bottom contour map.







The glow in the photograph is caused when gamma rays emitted by radioactive cobalt cylinders interact with the surrounding pool of water.

Gamma rays. The gamma-ray region of the electromagnetic spectrum coincides with the x-ray region. Gamma radiation is emitted by the unstable nuclei of natural or artificial radioactive materials. We shall return to considering gamma rays in Unit 6.

Q9 Why are radio waves not much affected by obstacles such as trees or buildings?

Q10 Why are relay stations often needed in transmitting television signals?

Q11 How is the frequency of x rays related to their penetration of matter?

Q12 How do the wavelengths used in RADAR compare to the wavelengths of visible light?

Q13 How does the production of x rays differ from that of gamma rays?

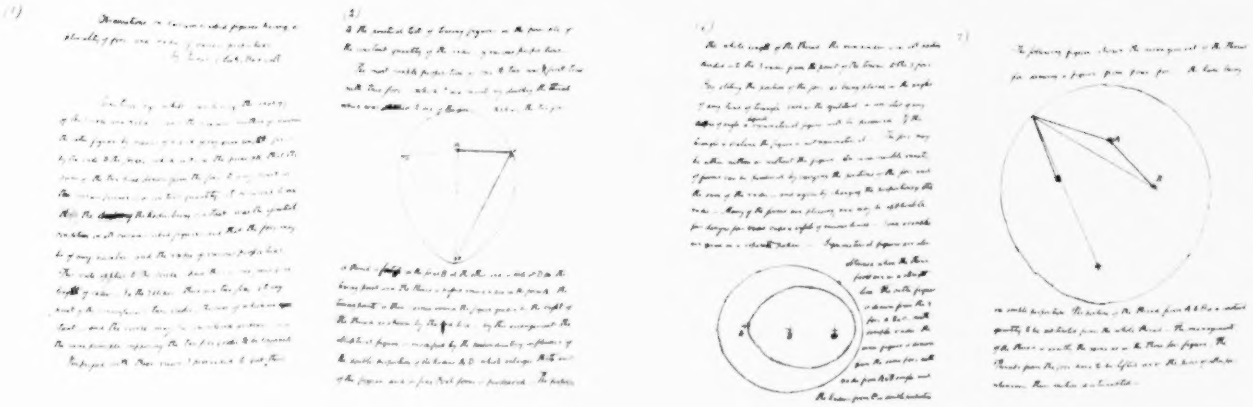
16.6 Maxwell: intellectual characteristics and attitudes. The capacity of Maxwell's electromagnetic theory to relate diverse discoveries over the broad frequency range of the electromagnetic spectrum is striking evidence of the importance and scope of his accomplishment. Let us consider some of the qualities of Maxwell's intellect that contributed to his success in carrying through his grand work.

SG 16.23

Maxwell's way of thinking about scientific problems was an effective joining of the concrete with the abstract. He was quick to see and grasp the essential physical features of the problems he attacked. His intuition developed from a practice he began as a boy of studying the operation of mechanisms, from a toy top to a commercial steam engine, until he had satisfied his curiosity about how they worked. On the abstract side, his formal studies, begun at the Academy in Edinburgh and continued through his work as an undergraduate at Cambridge, gave Maxwell experience in using mathematics to develop useful parallels among apparently unrelated occurrences.

Within two years after receiving his bachelor's degree, Maxwell demonstrated his exceptional ability to fuse these two elements. His paper "On Faraday's Lines of Force" gave mathematical form to a physical model. His prize-winning essay "On the Stability of the Motion of Saturn's Rings" was a mathematical analysis of several mechanical models by which he proved that only one model of the ring material could account for the stability of the rings.

Although Maxwell's theories were his greatest contributions to science, he did important experimental work on color, on



James Clerk Maxwell (1831-1879) was born in Edinburgh, Scotland in the same year Faraday discovered electromagnetic induction. Unlike Faraday, Maxwell came from a well-off family, and was educated at the Edinburgh Academy and the University of Edinburgh. He showed a lively interest in how things happened when he was scarcely three years old. As a child he constantly asked, "What's the go of that?". While Maxwell was still at the Edinburgh Academy, he wrote a paper on "Oval Curves," and a summary of this paper was published in the Proceedings of the Royal Society of Edinburgh when he was only fourteen years old. By the time he was seventeen he had published three papers on the results of his original research. In 1850 he went to the University of Cambridge in England. In 1856 he became Professor of Physics at the University of Aberdeen in Scotland. He was one of the main contributors to the kinetic theory of gases and to two other important branches of physics, statistical machines and thermodynamics. His greatest achievement was his electromagnetic theory. Because of his tremendous contributions, Maxwell is generally regarded as the greatest physicist between the time of Isaac Newton and that of Albert Einstein.

the viscosity of gases, and in electricity and magnetism. Maxwell was a strong believer in the value to the scientist of working at both theory and experiment.

> There is no more powerful method for introducing knowledge into the mind than that of presenting it in as many different ways as we can. When the ideas, after entering through different gateways, effect a junction in the citadel of the mind, the position they occupy becomes impregnable. ...It is therefore natural to expect that the knowledge of physical science obtained by the combined use of mathematical analysis and experimental research will be of a more solid, available, and enduring kind than that possessed by the mere mathematician or the mere experimenter.

In addition to working at physics itself, Maxwell was an active analyst of the methods of scientists and of the ways in which scientific knowledge progresses. He recommended the historical study of original works of science, believing that

SG 16.24

> It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in the nascent state...

Many of Maxwell's papers begin with reviews of earlier work that show the care with which he studied the history of his subject. Maxwell asserted that it was important for the scientist to know, through examples, the value of different scientific methods. In addition to studying procedures that have succeeded, the scientist should study those that have failed.

> But the history of science is not restricted to the enumeration of successful investigations. It has to tell of unsuccessful inquiries, and to explain why some of the ablest men have failed to find the key to knowledge, and how the reputation of others has only given a firmer footing to the errors into which they fell.

At a time when other physical scientists were saying that a mechanical explanation for physical experience was nearly complete, Maxwell saw new possibilities for scientific explanation and enlarged opportunities for scientific speculation. As with the Newtonian synthesis, a stimulating period of application and extension of Maxwell's new field theory followed. The theory of relativity (1905) put Maxwell's work in a new and wider framework. But eventually results accumulated that did not fit Maxwell's theory; something more was needed. In 1925, after a quarter century of discovery and improvisation, the development of the quantum

See "James Clerk Maxwell, Part II" and "Maxwell's Letters: A Collection" in Project Physics Reader 4.

theory led to an enlarged synthesis that included Maxwell's electromagnetism.

Q14 What value did Maxwell see in a scientist working at both theory and experiment?

Q15 What did he think important to study in the history of science?

16.7 What about the ether? The luminiferous ether had been postulated specifically to serve as a medium for the propagation of light waves. Maxwell found that the same ether could also be used to transmit electric and magnetic forces. Just before his death in 1879, Maxwell wrote an article for the Encyclopaedia Britannica, in which he supported the ether concept.

> Whatever difficulties we may have in forming a consistent idea of the constitution of the aether there can be no doubt that the interplanetary and interstellar spaces are not empty, but are occupied by a material substance or body, which is certainly the largest, and probably the most uniform body of which we have any knowledge....

Maxwell was aware of the failures of earlier ether theories. Near the beginning of the same article he said:

> Aethers were invented for the planets to swim in, to constitute electric atmospheres and magnetic effluvia, to convey sensations from one part of our bodies to another, and so on, till all space had been filled three or four times over with aethers. It is only when we remember the extensive and mischievous influence on science which hypotheses about aethers used formerly to exercise, that we can appreciate the horror of aethers which sober-minded men had during the 18th century...

Why, after he had succeeded in formulating his electromagnetic theory in a way that made it independent of any detailed model of the ether, did Maxwell continue to speak of the "great ocean of aether" filling all space?

Like other great men, Maxwell could go only so far in changing his view of the world. It was almost unthinkable that there could be vibrations without something that vibrates—that there could be waves without a medium. The verb "to wave" must have a subject: the ether. Similarly, to many nineteenth-century physicists the idea of "action at a distance" seemed absurd. How could one object exert a force on another body far away if something did not transmit the force? One body is said to act on another, with the word on conveying the idea of contact. Thus, according to accepted ways of describing the world using the common language, the postulate of the ether seemed necessary.

16.7

Yet twenty-five years after Maxwell's death the ether concept had lost much of its support, and within another decade, it was dropped from the physicists' collection of useful concepts.

In large part, the success of Maxwell's theory, with its indifference to details of the ether's constitution, helped to undermine the general belief in the existence of an ether. Maxwell's equations could be considered to give the relations between changes of electric and magnetic fields in space without making any reference to the ether.

Another reason for skepticism about the existence of the ether was the failure of all attempts to detect the motion of the earth with respect to the ether. If light is a kind of vibration of the ether, then light should travel at a definite speed relative to the ether. But it seemed reasonable to assume that the earth is moving through the ether as it makes its annual orbit around the sun. Under these conditions the speed of light should be observed to differ, when the earth and the light are moving in the same direction through the ether, from the speed when the earth and light are moving in opposite directions through the ether. An analogous effect is observed with sound waves that go faster with respect to the earth when traveling in the direction of the wind than they do when traveling against the wind.

When the time for light to make a round trip with and against the ether wind is computed and compared with the time calculated for a round trip in the absence of an ether wind, the expected time difference is found to be very small: only 10^{-15} seconds for a round trip of 30 meters. Although this is too short a time difference to measure directly, it is of the same order as the time for one vibration of visible light and might be detected from observations of an appropriately produced interference pattern. In 1887 the American scientists Michelson and Morley used a specially designed interferometer that was sensitive enough to measure an effect only one per cent as great as that expected on the basis of the ether theory. Neither this experiment nor the many similar experiments done since then have revealed an ether.

Michelson first tried the experiment in 1881, stimulated by a letter of Maxwell's published just after Maxwell's death.

In an attempt to preserve the idea of an ether, supporters of the ether concept offered various explanations for this unexpected negative result. For example, they even suggested that objects moving at high speeds relative to the ether might change their size in just such a way as to make this relative speed undetectable.

The conclusive development that led scientists to forego the ether concept was not a definitive experiment, but a brilliant argument by a young man of 26 years to the effect that a deep union of mechanics and electromagnetism could be achieved without the ether model. The man was Albert Einstein. A few remarks here describing his accomplishment will provide a setting for your study of Einstein's work now or at a later time. (More on relativity theory appears in Chapter 20 and Project Physics Reader 5.)

In 1905, Einstein showed how the laws of electromagnetism satisfy the same principle of relativity that holds for mechanics. The Galilean principle of relativity (Sec. 4.4) states that the same laws of mechanics apply in each of two frames of reference which have a constant relative velocity. Thus it is impossible, according to this principle, to tell by any kind of mechanical experiment whether or not one's laboratory (reference frame) is at rest or is moving with constant velocity. The principle is illustrated by the common experience that within a ship, car, plane or train moving at a constant speed in a straight line, the observer finds that objects move, or remain at rest, or fall or respond to applied forces in just the same way they do when these conveyances are at rest. Galileo, a convinced Copernican, used this principle to account for the common experience that the motion of objects with respect to the earth gives no indication that the earth itself is in motion about the sun

Einstein in 1912

In his 1905 paper Einstein considered what would happen if this principle of relativity applied to all of physics, including electromagnetism. He assumed that the speed of light in free space is the same for all observers, even when they are moving relative to each other or relative to the light sources. With this bold assumption Einstein rejected the ether and all other attempts to provide a preferred frame of reference for light. The price to be paid for making this assumption, Einstein showed, was the necessity of revising some commonly held and hence commonsense notions of space and time. By making these revisions, Einstein demonstrated that Maxwell's equations are fully consistent with the principle of relativity. As scientists came to recognize how the extension of the relativity principle to electromagnetism fitted the observed behavior of light and led to useful new ideas about mass and energy, they rejected the idea of the ether. Some of the important consequences of Einstein's theory of relativity will be discussed in Unit 5.

SG 16.26
SG 16.27

See Einstein's essay "On The Method of Theoretical Physics" in Project Physics Reader 4.

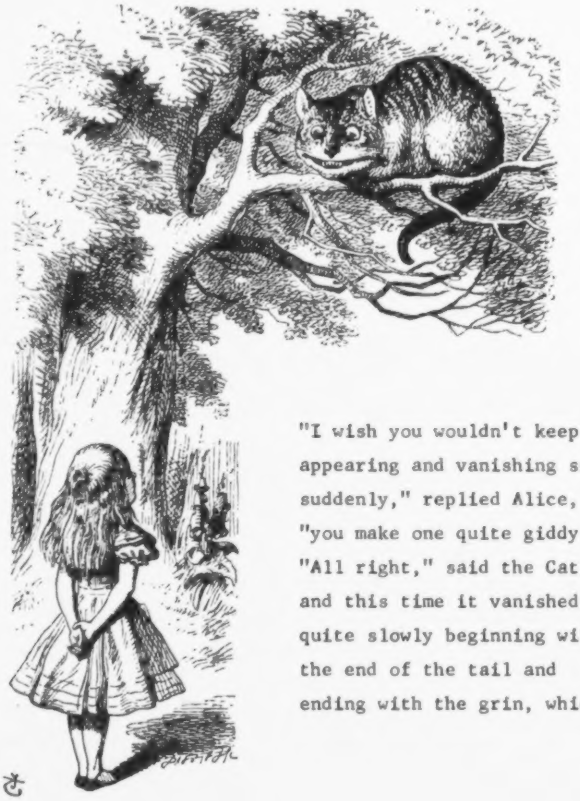
What was the role played by the elaborate array of ethers, vortices and other mechanical models that the nineteenth-century physicists used? It would certainly be unjust to say that the mechanical models were useless, since they guided the work of Maxwell and others and had astonishingly useful by-products in contributing to an understanding of the elastic properties of matter. We should consider the mechanical models of light and electricity as the scaffolding which is used to erect a building; once the building is completed, providing the construction is sound, the scaffolding can be torn down and taken away.

Indeed the whole conception of explanation by means of mechanism, while intuitively persuasive, has been found insufficient and has been abandoned. Important developments in twentieth-century physics that have demonstrated the inadequacy of mechanical explanation will be discussed in Units 5 and 6.

Q16 **Why did Maxwell and others cling to the concept of an ether?**

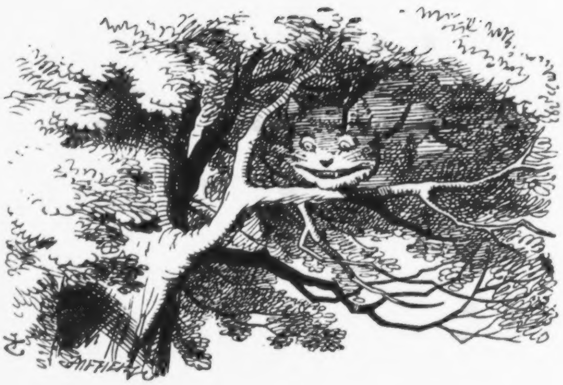
Q17 **Whose argument finally made the ether an unnecessary hypothesis?**

In this chapter you have read about how mechanical models of light and electromagnetism faded away, leaving a model-less mathematical field theory. The situation might be likened to that of the Cheshire Cat, in a story written by the Reverend Charles Dodgson, a mathematics teacher at Oxford, in 1862:



"I wish you wouldn't keep appearing and vanishing so suddenly," replied Alice, "you make one quite giddy." "All right," said the Cat; and this time it vanished quite slowly beginning with the end of the tail and ending with the grin, which remained some time after the rest of it had gone. "Well! I've often seen a cat without a grin," thought Alice, "but a grin without a cat! It's the most curious thing I ever saw in my life!"

(Alice's Adventures in Wonderland. Chapter VI)



16.1 What inspired Oersted to look for a connection between electricity and magnetism?

16.2 A current in a conductor can be caused by a steady electric field. Can a displacement current in an insulator be similarly caused? Explain your answer briefly.

16.3 How is an electromagnetic wave initiated and propagated?

16.4 What is the "disturbance" that travels in each of the following waves:
a) water waves,
b) sound waves,
c) electromagnetic waves?

16.5 If the velocity calculated from experiments measuring the charge on a capacitor is the same as the velocity of light, how do you account for the difference between 310,740,000 meters/sec and 314,858,000 meters/sec?

16.6 In Hertz's detector, it is the electric field strength in the gap between the ends of the wire ring that makes the sparks jump. How could Hertz show that the waves were vertically polarized?

16.7 What evidence did Hertz obtain that the sparking of his induction coil generated waves having many similar properties to light waves?

16.8 Give several factors that contributed to the twenty-five year delay in the general acceptance by scientists of Maxwell's electromagnetic wave theory.

16.9 What evidence is there for believing that electromagnetic waves carry energy?

16.10 What is the wavelength of an electromagnetic wave generated by the 60 cycles/sec alternating current in power lines?

16.11 How short are "short-wave" radio waves? (Look on the dial of a short-wave radio.)

16.12 Electric discharges in sparks, neon signs, lightning, and some atmospheric disturbances produce radio waves. The result is "static" or noise in radio receivers. Explain why FM radio is almost static-free.

16.13 Why is there federal control on the broadcast power and direction of radio and TV stations, but no comparable controls on the distribution of newspapers and magazines?

16.14 What information about earth-people would be available to extraterrestial beings?

16.15 Why can radio waves be detected at greater distances than the waves used for television and FM broadcasting?

16.16 The ideal relay satellite would have a 24-hour orbit. What would the radius of such a "synchronous" orbit be? (Refer to Unit 2 for whatever principles or constants you need.)

16.17 Explain why airplanes passing overhead cause "flutter" of a TV picture.

16.18 From the answers to questions 16.12 and 16.17, how do you think the TV picture information is carried? How is the TV sound information carried?

16.19 How much time would elapse between the sending of a radar signal to the moon and the return of the echo?

16.20 Refer to the black-and-white photograph on p. 122 that was taken using film sensitive only to the infra-red. How do you account for the appearance of the trees, clouds and sky?

16.21 What do you think is the reason that the eye is sensitive to the range of wavelengths that it is?

16.22 A sensitive thermometer placed in different parts of the visible spectrum formed by a quartz prism will show a rise in temperature. This shows that all colors of light produce heat when absorbed. But the thermometer also shows an increase in temperature when its bulb is in either of the two dark regions beyond the end of the spectrum. Why is this?

16.23 For each part of the electromagnetic spectrum discussed in Sec. 16.5, list the ways in which you have been affected by it. Give examples of things you have done with radiation in that frequency range, or of effects it has had on you.

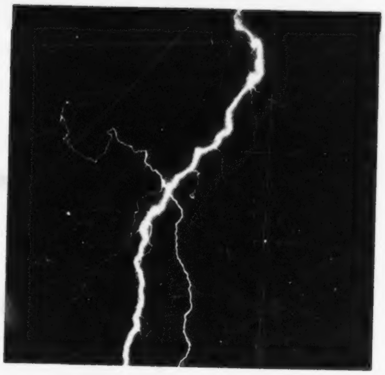
16.24 What reason did Maxwell give for studying original scientific memoirs? Do you agree with his statement?

16.25 What is a principal reason for the loss of support for the ether concept?

16.26 At many points in the history of science the "natural" or "intuitively obvious" way of looking at things has changed radically. Our attitudes toward action-at-a-distance are a case in point. What are some other examples?

16.27 Can intuition be educated? That is, can our feelings about what the fundamental aspects of reality are be changed? Use attitudes taken toward action-at-a-distance or the ether as examples.

16.28 Explain the analogy of the cat-less grin given at the end of Ch. 16.

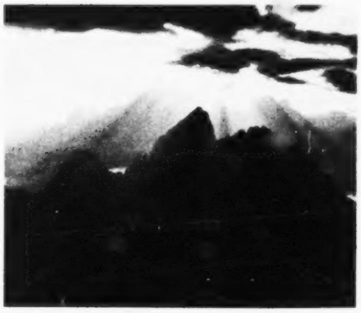


Epilogue We have seen how scientists sought to make light and electromagnetism comprehensible by devising models. The particle model accounted for the behavior of light by showing that moving particles, on experiencing strong forces at a boundary, will be bounced back or swerved in just the direction light is observed to be reflected and refracted. The wave model accounted for these and other effects by treating light as transverse waves in a continuous medium. Since there are material particles (sand grains, pebbles, projectiles) and waves (on strings, in water, etc.) that can be observed in action, these models provided a substantial, mechanical analogy for light corpuscles and light waves.

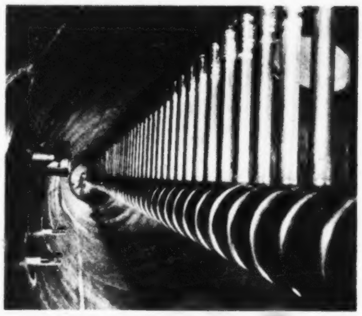
The same approach through mechanical analogy worked, up to a point, in explaining electricity and magnetism. Both Faraday and Maxwell made use of mechanical models for electric and magnetic lines of force. Maxwell used these models as clues and guides to the development of a mathematical theory of electromagnetism that, when completed, went well beyond the models. The electric and magnetic fields of Maxwell's theory cannot be made to correspond to the parts of any mechanical model. Is there, then, any way we can picture a field? Here is the response of the Nobel Prize-winning American physicist Richard Feynman:

> I have asked you to imagine these electric and magnetic fields. What do you do? Do you know how? How do I imagine the electric and magnetic field? What do I actually see? What are the demands of scientific imagination? Is it any different from trying to imagine that the room is full of invisible angels? No, it is not like imagining invisible angels. It requires a much higher degree of imagination to understand the electromagnetic field than to understand invisible angels. Why? Because to make invisible angels understandable, all I have to do is to alter their properties *a little bit*—I make them slightly visible, and then I can see the shapes of their wings, and bodies, and halos. Once I succeed in imagining a visible angel, the abstraction required—which is to take almost invisible angels and imagine them completely visible—is relatively easy. So you say, "Professor, please give me an approximate description of the electromagnetic waves, even though it may be slightly inaccurate, so that I too can see them as well as I can see almost invisible angels. Then I will modify the picture to the necessary abstraction."
>
> I'm sorry that I can't do that for you. I don't know how. I have no picture of this electromagnetic field that is in any sense accurate. I have known about the electromagnetic field a long time—I was in the same position 25 years ago that you are now, and I have had 25 years of experience thinking about these wiggling waves. When I start describing the magnetic field moving through space,

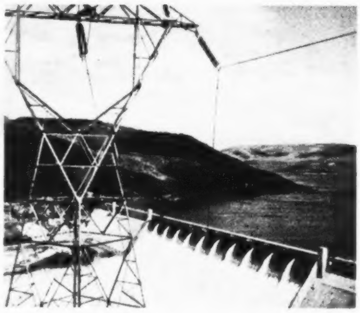
> I speak of the E- and B-fields and wave my arms and you may imagine that I can see them. I'll tell you what I see. I see some kind of vague shadowy, wiggling lines—here and there is an E and B written on them somehow, and perhaps some of the lines have arrows on them—an arrow here or there which disappears when I look too closely at it. When I talk about the fields swishing through space, I have a terrible confusion between the symbols I use to describe the objects and the objects themselves. I cannot really make a picture that is even nearly like the true waves. So if you have some difficulty in making such a picture, you should not be worried that your difficulty is unusual.
>
> (A more extended excerpt may be found in the Unit 4 Reader.)



We can summarize the general progression represented by the development of mechanics and electromagnetism by saying that physical theories have become increasingly abstract and mathematical. Newton banished the celestial machinery of early theories by substituting a mathematical theory using the laws of motion and the inverse-square law. Maxwell developed a mathematical theory of electromagnetism that, as Einstein showed, did not require any all-pervading material medium. We are seeing a growing disparity between common-sense ideas that develop from direct human experiences and the subtle mathematical abstractions developed to deal with effects that we cannot sense directly.



Yet these highly abstract theories do tell us about the things we can see and touch and feel. They have made it possible to devise the equipment that guides space probes to other planets and to design and operate the instruments that enable us to communicate with these probes. Not only are these theories at the base of all developments in electronics and optics, but they also contribute to our understanding of vision and the nervous system.



Maxwell's electromagnetic theory and the interpretation given to electromagnetism and mechanics by Einstein in the special theory of relativity produced a profound change in the basic philosophical viewpoint of the Newtonian cosmology. While we cannot yet give a comprehensive statement of these changes, some aspects of a new cosmology can already be detected. Before we can even hint at this new trend, we must give further attention to the behavior of matter and to the atomic theories developed to account for this behavior.

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Brief Answers to Unit 4 Study Guide

Chapter 13

13.1		7.5 cm
13.2	(a)	distance too small
	(b)	no
	(c)	large distances involved
	(d)	lower limit was achieved
13.3	(a)	4.4×10^9 m
	(b)	3.0×10^8 m/sec
	(c)	conjunction cycle
13.4		9.5×10^{15} m
13.5		4.3 yrs.; 28 times
13.6		path shown
13.7		36"
13.8		invisible
13.9		diagrams
13.10	(a)	diagram
	(b)	inverse with height
13.11	(a)	diagram
	(b)	$\frac{1}{2}mv^2$; $m\vec{v}_x = m\vec{v} \sin \theta$; $m\vec{v}_y = m\vec{v} \cos \theta$
	(c)	$\frac{1}{2}mv^2$ and $m\vec{v}_x$
	(d)	energy conservation
	(e)	$m\vec{u}_x = m\vec{u} \sin \theta_r$; $m\vec{u}_y = m\vec{u} \cos \theta_r$
	(f)	derivation
13.12		diagrams
13.13	(a)	$(m + \frac{1}{2})\lambda$
	(b)	red
	(c)	increased fringe separation
	(d)	same as (c)
	(e)	same separation
13.14		appears in bright fringes
13.15		constructive interference
13.16		6×10^{14} cps; 10^{10} times AM
13.17	(a)	no
	(b)	discussion
13.18		discussion
13.19		discussion

Chapter 14

14.1	(a)	tripled
	(b)	halved
	(c)	not changed
14.2		95 km
14.3		discussion
14.4		yes; positive
14.5	(a)	1.6 N/kg
	(b)	4.1×10^9 N/kg
	(c)	$g_r \propto r$
14.6		reaction to field, then to source
14.7	(a)	right
	(b)	down
14.8	(a)	10^6 coulombs
	(b)	10^{-9} coulombs/m^2
14.9		sketch (normal to surfaces)
14.10		help
14.11		6.25×10^{18} electrons
14.12		3.4×10^{42}
14.13	(a)	$\frac{1}{2}mv^2 = \frac{1}{2}kq^2/R$
	(b)	1.2×10^{-18}J
	(c)	1.5×10^6 m/sec
14.14		conductor
14.15		30 volts
14.16		zero
14.17		derivation
14.18	(a)	3×10^6 volt/meter
	(b)	10^7 volt/meter
14.19	(a)	12 volts
	(b)	zero
	(c)	12 volts
14.20	(a)	100 eV or 1.6×10^{-17}J
	(b)	5.6×10^6 m/sec
14.21	(a)	4 amps
	(b)	5 ohms
	(c)	15 volts
14.22	(a)	10^7 volts
	(b)	5×10^8 joules
14.23		discussion
14.24		20 watts
14.25	(a)	8 watts
	(b)	20 watts
	(c)	45 watts
14.26		compass can't respond
14.27		north
14.28		3 amps north
14.29	(a)	derivation
	(b)	v, B and R
14.30		derivation
14.31	(a)	derivation
	(b)	discussion
14.32		west

Chapter 15

15.1		discussion
15.2		yes
15.3		all except (d)
15.4		discussion
15.5	(a)	exercise
	(b)	upward
	(c)	downward

15.6 Lenz's law

15.7 outside magnet

15.8 opposite

15.9 discussion

15.10 (a) 1 amp
(b) 10 ohms
(c) burn out

15.11 (a) 1/12 amp
(b) 1440 ohms

15.12 (a) 1 amp, ½ amp
(b) 1/5 watt, 1/20 watt
(c) 0.97 amp, 0.19w, 5.6w;
0.50 amp, 0.05w, 6w.

15.13 5 amps

15.14 derivation

15.15 low voltage coil

15.16 discussion

15.17 discussion

15.18 report

15.19 discussion

15.20 sketch

Chapter 16

16.1 symmetry

16.2 no

16.3 accelerating charge, mutual induction

16.4 (a) height
(b) pressure
(c) field strength

16.5 measurement uncertainty

16.6 detector orientation

16.7 light properties

16.8 discussion

16.9 absorbtion effects, etc.

16.10 5×10^6 m

16.11 10 m to 10^2 m

16.12 frequency modulated

16.13 discussion

16.14 discussion

16.15 ionospheric reflection of shorter wavelength radiation

16.16 27,900 miles

16.17 phase difference between direct and reflected waves

16.18 AM; FM

16.19 2.6 sec.

16.20 absorbtion

16.21 evolution

16.22 UV and IR

16.23 discussion

16.24 discussion

16.25 unnecessary for mathematical description

16.26 discussion

16.27 discussion

16.28 body: mechanical models
grin: mathematical description

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Pp. 132, 133 John Tenniel drawings.

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Much of the historical information in Chapter 15, in particular the discussion of the ac-dc controversy, is based on the book by Harold I. Sharlin, The Making of the Electrical Age (Abelard-Schuman, New York, 1963). We are grateful to Professor Sharlin for giving his permission to use this material.

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Answers to End of Section Questions

Chapter 13

Q1 Diffraction effects become greater as a slit is made increasingly narrow, spreading the light into a diverging beam.

Q2 Römer based his prediction on the extra time he had calculated it would require light to cross the orbit of the earth.

Q3 Römer had shown that light does have a finite speed.

Q4 Experiments carried out by Foucault and Fizeau showed that light has a lower speed in water than in air, whereas the particle model required that light have a higher speed in water.

Q5 When light enters a more dense medium, its wavelength and speed decrease, but its frequency remains unchanged.

Q6 Young's experiments showed that light could be made to form an interference pattern, and such a pattern could be explained only by assuming a wave model for light.

Q7 It was diffraction that spread out the light beyond the two pinholes so that overlapping occurred and interference took place between the two beams.

Q8 Poisson applied Fresnel's wave equations to the shadow of a circular obstacle and found that there should be a bright spot in the center of the shadow.

Q9 Newton passed a beam of white light through a prism and found that the white light was somehow replaced by a diverging beam of colored light. Further experiments proved that the colors could be recombined to form white light.

Q10 Newton cut a hole in the screen on which the spectrum was projected and allowed a single color to pass through the hole and hence through a second prism: he found that the light was again refracted but no further separation took place.

Q11 A coat appears yellow if it reflects mainly yellow light and absorbs other colors of light.

Q12 The "nature philosophers" were searching for unifying principles and were very unhappy with the idea that something they had regarded as unquestionably pure had many components.

Q13 The amount of scattering of light by tiny obstacles is greater for shorter wavelengths than for longer wavelengths.

Q14 The "sky" is sunlight scattered by the atmosphere. Light of short wavelength, the blue end of the spectrum, is scattered most.

Q15 Hooke and Huygens had proposed that light waves are similar to sound waves: Newton objected to this view because the familiar straight-line propagation of light was so different from the behavior of sound. In addition, Newton realized that polarization phenomena could not be accounted for in terms of spherical pressure waves.

Q16 "Unpolarized" light is a mixture of waves polarized in various directions.

Q17 Light had been shown to have wave properties, and all other known wave motions required a physical medium to transmit them, so it was assumed that an "ether" must exist to transmit light waves.

Q18 Because light is a transverse wave and propagates at such a high speed, the ether must be a very stiff solid.

Chapter 14

Q1 He showed that the earth and the lodestone affect a magnetized needle in similar ways.

Q2 Amber attracts many substances; lodestone only a few. Amber needs to be rubbed to attract; lodestone always attracts. Amber attracts towards its center; lodestone attracts towards either of its poles.

Q3 A cork hung inside a charged silver can was not attracted to the sides of the can. (This implied that there was no net electric force on the cork—a result similar to that proved by Newton for gravitational force inside a hollow sphere.)

Q4 $F_{el} \propto 1/R^2$ and $F_{el} \propto q_A q_B$

Q5 F_{el} will be one quarter as large.

Q6 No, the ampere is the unit of current.

Q7 No, induced charges could account for this behavior.

Q8 Each point in a scalar field is given by a number only, whereas each point in a vector field is represented by a number and a direction.

Q9 a) the same direction as the gravitational force on a test mass placed at that point
b) the same direction as the electric force on a positive test charge at that point.

Q10 The corresponding forces would also be doubled and therefore the ratios of force to mass, and force to charge, would be unchanged.

Q11 If the droplets or spheres are charged negatively, they will experience an electric force in the direction opposite to the field direction.

Q12 Charge comes in basic units: the charge of the electron.

Q13 Franklin observed that unlike charges can cancel each other and he therefore proposed that negative charges are simply a deficiency of positive charges.

Q14 It produced a steady current for a long period of time.

Q15 The voltage between two points is the work done in moving a charge from one point to the other, divided by the magnitude of the charge.

Q16 No; the potential difference is independent of both the path taken and the magnitude of the charge moved.

Q17 An electron-volt is a unit of energy.

Q18 If the voltage is doubled the current is also doubled.

Q19 The electrical energy is changed into heat energy and possibly light energy. (If the current is *changing*, additional energy transformations occur; this topic will be discussed in Chapter 16.)

Q20 Doubling the current results in four times the heat production (assuming the resistance is constant).

Q21 The charges must be moving relative to the magnet. (They must in fact be moving *across* the field of the magnet.)

Q22 It was found to be a "sideways" force!

Q23 Forces act on a magnetized (but uncharged) compass needle placed near the current.

Q24 Ampère suspected that two currents should exert forces on each other.

Q25 b), c), d).

Q26 b), c), e).

Q27 The magnetic force is not in the direction of motion of the particle—it is directed off to the side, at an angle of 90° to the direction of motion.

Chapter 15

Q1 The single magnetic pole is free to move and it follows a circular line of magnetic force around the current carrying wire.

Q2 electric currents circulating within the magnets

Q3 electromagnetic induction

Q4 the production of a current by magnetism

Q5 The first current must be changing.

Q6 the Faraday disc dynamo

Q7 The loop is horizontal for maximum current, vertical for minimum.

Q8 It reverses the connection of the generator to the outside circuit at every half turn of the loop.

Q9 Use a battery to drive current through the coil.

Q10 Batteries were weak and expensive.

Q11 An unknown workman showed that Gramme's dynamo could run as a motor.

Q12 too glaring, too expensive, too inconvenient

Q13 an improved vacuum pump

Q14 A small current will have a large heating effect if the resistance is high enough.

Q15 There is less heating loss in the transmission wires.

Q16 A current is induced in the secondary coil only when there is a *changing* current in the primary coil.

Chapter 16

Q1 a magnetic field

Q2 the small displacement of charges that accompanies a changing electric field

Q3 the relations between electric and magnetic fields

Q4 the ratio of the values of a quantity of charge measured electrically and magnetically

Q5 The speed of electromagnetic waves turned out to be, within the limits of experimental error, the same as the speed of light.

Q6 the existence of electromagnetic waves

Q7 a loop of wire

Q8 Electromagnetic waves exert pressure on any surface that reflects or absorbs them.

Q9 They have very great wavelengths (from tens to thousands of meters).

Q10 The signals travel in nearly straight lines and would otherwise pass into space instead of following the earth's curvature.

Q11 The higher the frequency, the greater is their penetration of matter.

Q12 10^5 times larger

Q13 X rays are produced by the sudden deflection or stopping of electrons; gamma radiation is emitted by unstable nuclei of radioactive materials.

Q14 He held that knowledge is more enduring if achieved in more than one way.

Q15 experiments and procedures that have failed, as well as those that were successful

Q16 It was almost unthinkable that there could be waves without a medium to transmit them.

Q17 Albert Einstein's (in his theory of relativity)